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THESIS

SYSTEMS ENGINEERING APPROACH FOR CONCEPTUAL DESIGN OF FRIGATE

by

Kwong Yang Lua

September 2015

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The Topside Sizing Model (TSM) is introduced and added to the Numerical Warship Design Procedure to find feasible and satisfactory conceptual ship designs. This thesis also provides guidance to ship topside designers in the methodology of integrating weapon and platform systems onboard a surface ship. A spiral model for Integrated Topside Design (ITD) is introduced and explained.

Lastly, this thesis uses NPS capability engineering for its cost-effectiveness model to examine several design alternatives and trade-offs in the capability of the frigate versus its cost of procurement.

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SYSTEMS ENGINEERING APPROACH FOR CONCEPTUAL DESIGN OF FRIGATE

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
ASW	Anti-Submarine Warfare
ASuW	Anti-Surface Warfare
ASIST	Aircraft Ship Integrated Secure and Traverse System
ATTD	Area Terminal Type Defense
AOA	Analysis of Alternative
AWS	Amphibious Warfare Ships
BAM	Blocking Assessment Model
BI	BlueIntercept
BOA	Beam Overall
BOE	Back of the Envelope
C	Center
C4I	Command, Control, Communications, Computers, and Intelligence
CDR	Critical Design Review
CFD	Computational Fluid Dynamics
CM	Counter Measures
CMS	Combat Management System
CONOPS	Concept of Operations
CS	Combat System
DOD	Department of Defense
DOE	Design of Experiments
EEZ	Exclusive Economic Zone
EM	Electromagnetic

EMI/EMC	Electromagnetic Interference/Electromagnetic Compatibility
ESM	Electronic Support Measures
FAT	Factory Acceptance Test
FEA	Finite Element Analysis
FCR	Fire Control Radar
FEM	Finite Element Method
FFBD	Functional Flow Block Diagram
FWD	Forward
HAT	Harbor Acceptance Test
HELIVAS	Heli Visual Aids System
HERF	Hazards of Electromagnetic Radiation to Fuel
HERO	Hazards of Electromagnetic Radiation to Ordnance
HERP	Hazards of Electromagnetic Radiation to Personnel
HM&E	Hull, Mechanical, and Electrical
ICS	Integrated Communication System
INS	Integrated Navigation System
ITD	Integrated Topside Design
LFT	Live Fire Test
LOA	Length Overall
LWL	Length at the Waterline
MIT	Massachusetts Institute of Technology
MLS	Missile Launch System
MOE	Measure of Effectiveness
MoM	Method of Moment

MOP	Measure of Performance
NPS	Naval Postgraduate School
NTZ	Non-Transmit Zone
PDR	Preliminary Design Review
RADHAZ	Radiation Hazards
RAM	Radar Absorbent Material
RAS	Refueling at Sea
RCS	Radar Cross Section
SAM	Surface-to-Air Missiles
SAT	Sea Acceptance Test
SEP	Systems Engineering Process
SSM	Surface-to-Surface Missiles
STBD	Starboard
TCCA	Transport Canada Civil Aviation
TSM	Topside Sizing Model
UAV	Unmanned Aerial Vehicle
UCL	University College London
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
VERTREP	Vertical Replenishment

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EXECUTIVE SUMMARY

This thesis is based on a systems engineering approach and design methodology with topside considerations and cost-capability analysis in designing and selecting a cost-effective conceptual frigate design that meets all the measures of effectiveness (MOEs). The systems engineering approach ensures that the stakeholders' requirements are fulfilled. Based on the mission needs, different sets of payload configuration can be inserted and evaluated using the design methodology to derive satisfactory conceptual ship designs. The topside sizing model improves the topside layout by enabling divergent thinking to generate new ship designs and, at the same time, incorporating topside design considerations.

Using Minitab, factorial analysis was performed to determine the impact of the various defense attributes on the performance of the overall defense (average number of leakers that target the AWSs per run). This allowed for the identification of attributes that have higher leverage on performance.

From the results of a Back of the Envelope (BOE) simulation, it can be seen that the existing defense payload configuration is insufficient to protect five frigates and four AWS from a swarm of 200 missiles. A Design of Experiments (DOE) result suggests that the kill probability of the BlueIntercept missile and RCS have a significant impact in defending and protecting the frigates and AWS in surviving the swarm attack of the RedFire missiles.

An assessment of all the 41 alternatives with calculated costs, different combination of payloads, and system effectiveness is analyzed. From the cost-effectiveness plot, Option 34, the baseline payload configuration with the only an upgrade to surveillance radar model 2 (higher sensor detection range) and to ATTD model 3 (higher probability of kill at 0.8 and range at 12 kyds), is the recommended solution. This option fulfilled the MOEs at the lowest cost of $618.925M per frigate. It is recommended that the detection range of surveillance radar and the ATTD be upgraded. This would enable the fleet to survive the swarm of RedFire missile attacks. The analysis

provides stakeholders with a quantitative evaluation of costs and capabilities of the vessel in order to suit it for the required mission needs.

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I would like to express my sincere gratitude to my thesis advisor, Professor Fotis Papoulias, and my second reader, Professor Clifford Whitcomb, for their support, patience, and guidance in my thesis writing.

Professor Papoulias was patient and accommodating during the thesis process, and his guidance helped make for a more coherent paper. His abilities to provide innovative ideas for my thesis and to pick out salient points have aided me tremendously in finding a proper focus for this paper.

I would also like to thank Professor Matthew Boensel for his valuable teaching in capability engineering, which provides my thesis a cost-capability analysis to evaluate the different ship design alternatives.

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I. INTRODUCTION

A. MOTIVATION

New naval ship designs are usually created in response to needs, such as the onset of new technologies, new operational requirements, changes in world politics, and lessons learned. These needs are identified by the stakeholders (e.g., naval planners) and are used as a basis for new naval ship design development. Ship designers must deal with a variety of stakeholders' requirements, and operating and maintenance concepts. They must take all of these inputs into their design considerations, explore alternatives, and later demonstrate to stakeholders their proposed design alternatives that meet the required functional and operational needs. In the process, they introduce and explain to the stakeholders the trade-offs and feasible design regions.

During the exploration of feasible designs, a lot of information about the ship structure, platform system, and combat system remains unknown/minimal/vague information to the designers, which poses great challenge to the overall ship design. These new naval ship design alternatives can take a long time to design. The proposed conceptual ship design alternatives may not be capable of meeting all of the stakeholders' requirements.

The ship and its topside designs are usually based on previous experience, lessons learned, and advice from chief designers. During initial conceptual design, assumptions have to be made and extra space margins have to be catered for items with uncertainty. A systems engineering design approach for both ship and its topside design can be introduced to assist ship designers at the conceptual design stage. Thus, the preliminary ship weight, dimensions, and topside size of a naval vessel can be approximated and determined based on the payload configuration, such as weaponry and electronics. It is also important to conduct the overall ship designs in conjunction with such analyses as ship stability, speed, power, and system availability studies to demonstrate the feasibility of its design.

Hopefully, this systems engineering approach will help ship designers improve their ships and topside designs in a short time. In the future, as ship designs and systems become more complex in accordance with higher stakeholder requirements, there will always be increased challenges in the design of the ship and its topside.

B. OBJECTIVES

The thesis is centered on the conceptual design of a frigate. During this conceptual design phase, there are general stakeholders' needs (e.g., operational requirements) of the frigate. This conceptual design stage has many different feasible design solutions. It is important at this stage that the ship designer has a method to enable the consideration of all the topside issues because these can drive the overall size of the ship (Brown 1987).

The main objective of this work is to propose a systems engineering approach to assist the ship designer understand the stakeholders' needs and values, design parameters, and evaluate various design alternatives during the conceptual design stage.

C. LITERATURE REVIEW

A literature review was conducted prior to the commencement of this thesis. This thesis extends the work from two University of College London (UCL) theses, one by Jonathan Andrew Bayliss (2003) and the other by Timothy Patrick McDonald (2010).

The ship design process is iterative, like a spiral model (Evans 1959), towards an efficient design. The capabilities needs of the required ship are identified, and the design is refined to meet needs as the concept develops. The first portion of this thesis applies a systems engineering approach in the ship design process, as in the work done by Choi (2009), Letourneau (2009), Gaitan (2011), Fox (2011), and Bahlman (2012).

The first thesis (Bayliss 2003) dealt with a methodology for topside design and integration in conceptual warship design. The thesis includes the UCL Numerical Warship Design Procedure, which derives a balanced frigate design with weight, volume, and principal dimensions. There is also a similar mathematical model for the design of naval vessel frigates (Graham and Hamly 1975). However, these two mathematical models do not include any topside layout, topside design considerations, or sizing, nor does it include a preliminary topside physical feasibility check. Thus, this thesis extends Bayliss's (2003) previous work by adding a topside sizing model, which provides a more accurate and satisfactory conceptual ship design to allow for better vessel cost forecasting.

The second thesis (McDonald 2010) introduces cost capability analysis, which explores the impact of payload and requirements on different platforms through the Numerical Warship Design Procedure. However, this thesis uses NPS Capability Engineering for the cost capability analysis portion through the Numerical Warship Design Procedure with the topside sizing model (as an add-on) for design concept selection.

D. SCOPE OF THESIS WORK

The scope of this thesis work is presented in four chapters:

Chapter II addresses the systems engineering approach, which includes needs identification, scenario development, functions, and requirements of the frigate.

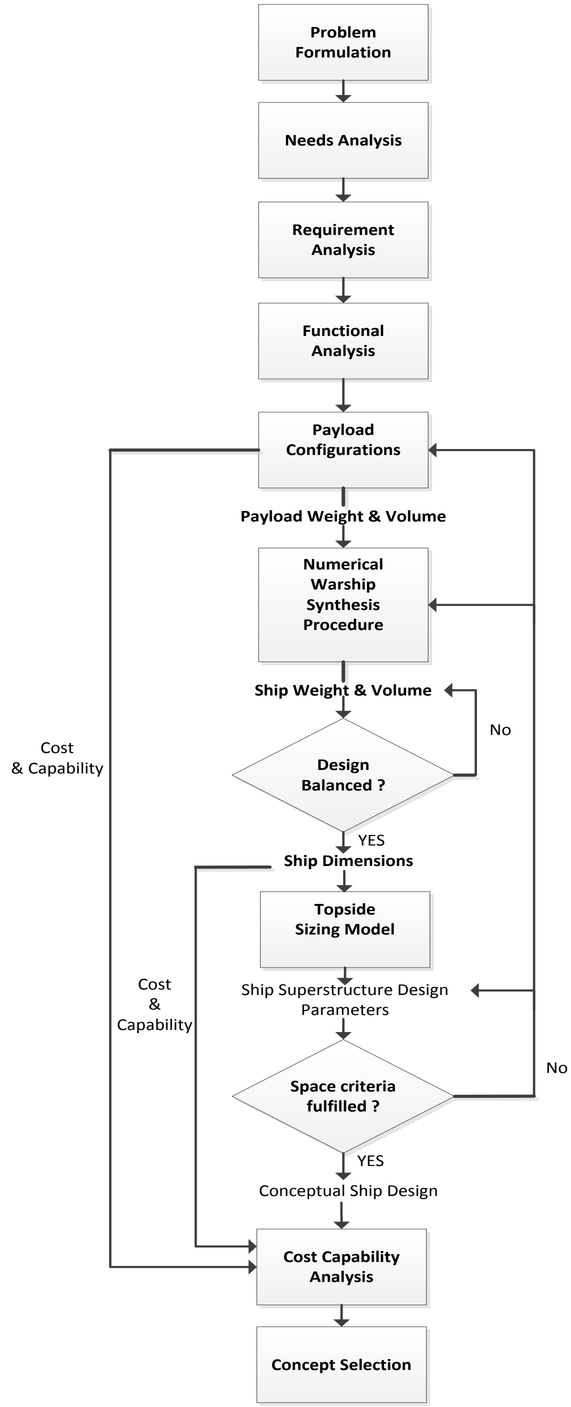
Chapter III details the spiral model for Integrated Topside Design (ITD) and the topside design considerations

Part 1 of Chapter IV details the design stage, which evaluates the impact of payload on the ship dimensions using UCL Numerical Warship Design Procedure. Part 2 of the design stage investigates the size of the topside and includes topside design considerations using the Topside Sizing Model. The ship synthesis model considers only monohull vessels. The study of other hull forms is not considered and could be recommended for future research.

Chapter V illustrates the cost capability analysis using NPS Capability Engineering. Lastly, from the analysis of alternatives (AOA), several feasible solutions that meet the overall measures of effectiveness (MOEs) are proposed and evaluated.

Figure 1 shows the overview of this thesis in terms of the flow of the systems engineering approach for the conceptual design of a frigate.

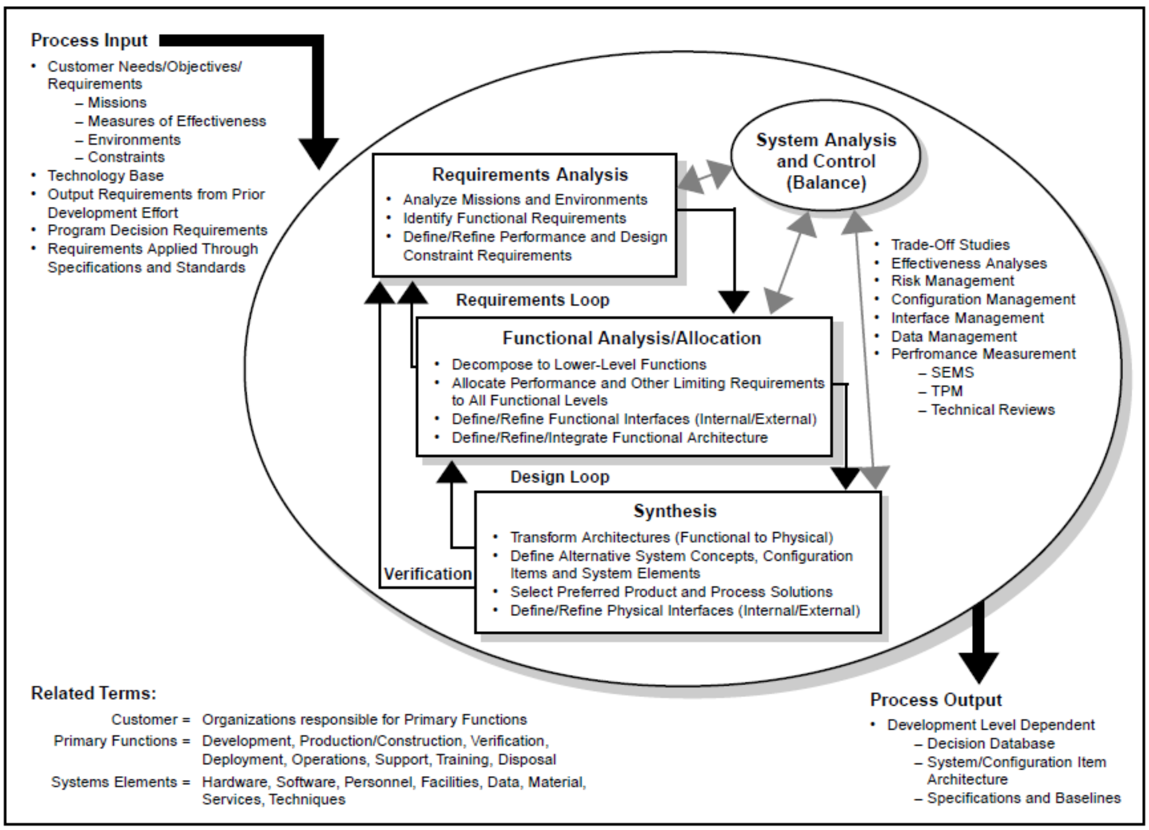
Figure 1. Overview of Systems Engineering Approach



II. SYSTEMS ENGINEERING APPROACH FOR CONCEPTUAL DESIGN OF FRIGATE

The Systems Engineering Process (SEP; Defense Acquisition University [DAU] 2001), displayed in Figure 2, is applied to this conceptual design of the frigate to result in a more desirable and satisfactory outcome. It is a comprehensive and iterative problem-solving process. The SEP is to first define the problem, determine the effective needs, and then develop a solution.

Figure 2. Systems Engineering Process



From Defense Acquisition University (DAU), *System Engineering Fundamentals*, Fort Belvoir, VA: Defense Acquisition University Press, 2001.

A good systems engineering approach requires an agreed problem and boundaries shared by stakeholders. The problem has to be identified and determined by the end user.

The end user and all the relevant stakeholders must discuss and agree on the problem and the possible solutions. The problem statement for this thesis is identified in Figure 3.

Figure 3. The Problem Statement

The problem is that the end user (Navy) is concerned about the increasing asymmetric threats within the maritime/littorals environment, particularly swarm missiles and unmanned aerial vehicles (UAVs).

Stakeholder analysis consists of three components: (1) identifying stakeholders and defining their roles in system development and use; (2) researching stakeholder documents to analyze their needs; and (3) performing interviews and engaging in two-way communications about requirements. A stakeholder can be the owner of the ship (Navy), project manager, weapons and defense system contractors/manufacturer, shipyard, contractor trainer and operator who have interests in the project. The stakeholders have different perspectives of the system and can affect/change the ship system's requirements. Stakeholder analysis has to be carried out to understand the stakeholders' effective needs and wants with respect to the problem. The stakeholders must communicate effectively and understand the needs of the end user, which is currently a capability gap within the littoral environment. The system dynamics, such as the boundaries, interactions with stakeholders, constraints, assumptions, limitations, and scope of the project, are first examined and thought through in order to provide the system with an effective need. The problem statement is then revised to the effective need, as shown in Figure 4.

Figure 4. The Effective Need

The effective need is a new fleet of five multi-roles stealth frigates required by the end user (Navy) to confront both conventional and asymmetric threats, especially swarm missiles/UAVs, within the maritime/littoral environment.

In the needs analysis phase, operational needs and requirements are required to be identified by the stakeholders and must exist for the new system (five multi-roles stealth frigates) (Kossiakoff and Sweet 2002).

With the clearly defined effective need, requirement analysis shall be performed to analyze the projected needs for the new system, determine what the operational objectives are, and determine the concept of operations (CONOPS) of the end user. A CONOPS for the system that is the new fleet of five multi-role stealth frigates is developed by the end user. The CONOPS describes the use of system solution and its context. The primary objective of the CONOPS was to ensure all stakeholders of the operational objectives and requirements. The CONOPS for the new fleet of multi-role stealth frigates that have been designated by the stakeholders are anti-air warfare (AAW), anti-surface warfare (ASuW), and anti-submarine warfare (ASW). These frigates shall be specifically optimized for the AAW role to counter the swarm missiles and UAVs. Some of the key design considerations will definitely be the surface-to-air missiles (SAM) system (primary anti-air weapon), and the secondary anti-air weapon will be the main gun system. The frigates shall also be equipped with an area terminal type defense (ATTD) system and a counter measures (CM) system to improve their survivability against swarm missiles and UAVs. The primary sensors for AAW are the electronic support measures (ESM), long-range surveillance radar for search and detection of threats, and fire control radar (FCR) for precise target tracking purposes. The system performance will be characterized by the survivability of the frigates against the swarm missiles and UAVs. The system's CONOPS are to be discussed with all the stakeholders to clarify the operational scenario of the system.

Scenarios are thought of from the CONOPS, which highlights some of the issues that arise should certain components of the system fail. The following scenarios (as shown in Appendix A and vignettes) are highly possible once the system is put in place. The system (new fleet of multi-role stealth frigate) should be adequately prepared for them. These scenarios enable the system engineers and ship designers to consider the alternatives solution later during the design phase.

After understanding the needs, CONOPs, and constraints of the stakeholders, functional analysis has to be performed for the operational objectives of the system to be translated into desired functions. The functional analysis phase of the systems engineering process allows individual component functions of a concept to be determined and then later developed further into the means to execute the functions in an operational environment. Functional decomposition is performed to breakdown the functions requirements into sub-function forms. The functional architecture of the system is, first, defining all the pertinent high-level functions; second, decomposing the functions into logical groupings of “high-level” and “derived” functions; third, organizing the functions into appropriate model diagrams that indicate the logical ordering or relation of functions; and fourth, performing an analysis of the functional architecture in order to understand what would need to be accomplished by the entire system of systems to make the solution concept valid.

As stated earlier, the scenarios are developed to help stakeholders understand what possible functions would be essential to the operation of the AAW. When the functional hierarchy for the AAW was developed using Vitech *Core*, the functions were then implemented into the operational scenario to determine the functional sequencing. The functional flow block diagram (FFBD; Blanchard and Fabrycky 2011) can be created to show how component functions are implemented in the scenario and determine whether there are missing functions that need to be developed.

As illustrated in Figures 19–23 of Appendix B, by decomposing the functions, many pertinent features of the AAW system could be derived, and these insights can be used to generate accurate system requirements. This provides a good skeleton of the system where other sub-functions can be built. Further decomposing the functions provided even more insights into the plausible methods of solving the problem.

The functions are assigned to a measure of performance (MOP), its respective measures, and a design goal after discussion review with stakeholders. *Measures* are properties, traits, and attributes that are qualitatively and quantitatively determinable. Langford (2012, pg 363) states that “*Metrics* are key to ultimately defining the system, establishing meaningful and verifiable requirements, and testing the system.” Therefore, it is important to define the metrics completely and accurately for the system development life cycle.

- MOE is a measure which expresses the extent of a system achieves its objectives/missions/tasks under specified conditions (Kossiakoff and Sweet 2002). An example of MOE can be probability of mission accomplishment.

- MOP is a quantitative measure of a system's capabilities or specific performance function (Kossiakoff and Sweet 2002). An example of MOP can be the percent of successful hits, missile speed.

The Navy is concerned about the survival of its high valued assets. The MOE for this thesis is **the survivability of Frigates and AWS.** This would be translated to the list of MOP in Table 1.

The number of frigates and AWS sunk would directly measure the overall defense capability of the naval fleet. This depends on the ability of SAM, main gun, decoy, and ATTD systems to intercept incoming threats. From the MOP, the functions identified should be traceable back to requirements. The system requirements are allocated to all functional levels. The system requirements that are derived from the functions shall also be mapped to the needs of the stakeholders. This is an iterative process of checking the basic system requirements against the stakeholders' needs. The mapping enables the system engineers and ship designers to verify whether all stakeholders' needs are being addressed by the system requirements.

In the synthesis phase, the functional architecture is mapped to the physical architecture, as shown in Table 7 in Appendix B. The functions identified earlier are allocated and mapped to high level objects/system. Physical decomposition is performed for the higher level system and broken down into its sub-entities. From the decomposition effort, alternative designs can be developed. The payload configuration versus mission capabilities can now be generated, as shown in Appendix C. AOA can then be performed before a solution is implemented. The selected solution are verifiable to the set of requirements, and the end results are validated as an acceptable solution to the agreed-upon problem.

Table 1. Summary of Measure of Effectiveness and Measure of Performance

No	Measure of Performance (MOP)	Objective	Descriptions
1	Number of RedFire Missile intercepted by SAM	To Maximize	The number of RedFire Missile intercepted is used as a measure of the BlueIntercept System's (1st layer of defense) ability to engage and destroy them.
2	Number of BlueIntercept Leakers targeting frigates	To Minimize	The number of BlueIntercept Leakers targeting at frigates has a direct relationship with the number of incoming threats destroyed by the system. The number of BlueIntercept Leakers targeting frigates is used as a measure of the BlueIntercept System's (1st layer of defense) ability to engage and destroy incoming threats.
3	Number of BlueIntercept Leakers targeting AWS	To Minimize	The number of BlueIntercept Leakers targeting AWS has a direct relationship with the number of incoming threats destroyed by the system. The number of BlueIntercept Leakers targeting AWS is used as a measure of the BlueIntercept System's (1st layer of defense) ability to engage and destroy incoming threats.
4	Number of RedFire Missile intercepted by Main Gun	To Maximize	The number of RedFire Missile intercepted is used as a measure of the Main Gun's (2nd layer of defense) ability to engage and destroy them.
5	Number of RedFire Missile attracted by Decoy	To Maximize	The number of RedFire Missile intercepted is used as a measure of the Decoy's (countermeasure) ability to attract them.
6	Number of RedFire Missile intercepted by ATTD	To Maximize	The number of RedFire Missile intercepted is used as a measure of the ATTD's (3rd layer of defense) ability to engage and destroy them.
7	Number of ATTD Leakers	To Minimize	The number of ATTD Leakers has a direct relationship with the number of frigates and AWS sunk and the ship survivability. The number of ATTD Leakers is used as a measure of the defenses of the frigates and AWS.
No	**Measure of Effectiveness (MOE)**	**Objective**	**Descriptions**
1	Survivability of frigates	To Maximize	This measure reflects the survivability of the asset against incoming threat.
2	Survivability of Amphibious Warfare Warships (AWS)	To Maximize	This measure reflects the survivability of the asset against incoming threat.

From Matthew Boensel, Capability Engineering [Lecture notes], Department of Systems Engineering, Naval Postgraduate School, Monterey, CA, 2015.

III. INTEGRATED TOPSIDE DESIGN

A. OVERVIEW

Integrated Topside Design (ITD) is a complex task in designing and shaping the topside superstructure and at the same time optimizing the locations of all necessary topside equipment on the weather deck and superstructure of a naval vessel to minimize interactions.

The topside of a warship must be able to accommodate a wide array of combat systems (CS); command, control, communications, computers, and intelligence (C4I); and hull, mechanical, and electrical (HM&E) functions while maintaining maximum functionality and performance of all systems for their intended missions (Baron et al. 2002). This is achieved by identifying and reducing risks of interference related to equipment on board a warship. Additionally, the ITD effort is to make explicit any radiation hazards onboard the vessel.

At the same time, the topside of the ship must continue serving the basic ship operational functions, such as vertical replenishment (VERTREP), refueling at sea (RAS), flight operations, small boat deployment, docking and maneuvering, personnel movement, and even deployment of mission modules, all while meeting overall ship signature requirements and imposing minimal manning and mission requirements.

The objectives of this ITD chapter are for ship designers to (1) maximize combat system operability, maintainability, and functionality; (2) understand and check for unforeseen problems that can be identified early in the initial design conceptual and preliminary phase of the ship using the Topside Design Checklist; and (3) size the topside superstructure using the Topside Sizing Model.

B. CHALLENGES FACED BY TOPSIDE DESIGNERS

The current process for designing and procuring a new naval vessel is time consuming. The following is a brief outline of the stages involved in naval shipbuilding:

1. Conceptual or tender phase

2. Contractual phase
3. Preliminary design review (PDR) phase
4. Critical design review (CDR) phase
5. Production phase
6. Harbor Acceptance Test (HAT)
7. Electromagnetic interference/electromagnetic compatibility (EMI/EMC) trial
8. Sea Acceptance Test (SAT)
9. Live Firing Test (LFT), if part of the agreed contract stated for the vessel
10. Operation phase
11. Disposal phase

At the conceptual phase, based on preliminary requirements given by the stakeholders, the first challenge is to have the topside designers design and position many weapons, electromagnetic (EM) radiators, and platform hardware on the topside of the warship. Their constraints are the limited real estate and the weight of the naval ship.

The second challenge is that the topside of a naval ship contains typically 30 to 50 antenna systems, which are placed in close proximity to each other. This raises the problem of EMI, which causes performance degradation of the antenna systems, blockage of communication channels, and even burn-out of inadequately protected equipment. The topside designers need the topside equipment specification information for ITD analysis. However, this information is usually available only at a later design stage, such as after contract signing of equipment. At times, the information can be obtained from the system supplier earlier and upon requests by the defense office or shipyard. Based on preliminary suppliers' equipment specification information, design experience, and databases, the topside designers then design a preliminary topside layout and generate a preliminary ITD analysis. The detailed ITD analysis and calculation can begin only when all the equipment specification information is available.

The third challenge is positioning, shaping, and sizing the choice of material of the topside superstructure especially for the forward (fwd) and aft mast.

During the CDR phase, there may be stakeholder needs to redesign the topside layout in terms of reshaping the structure, repositioning, and even placing additional topside equipment. However, at this phase, most of the HM&E designs have already been finalized. This results in time and cost implications to the overall project.

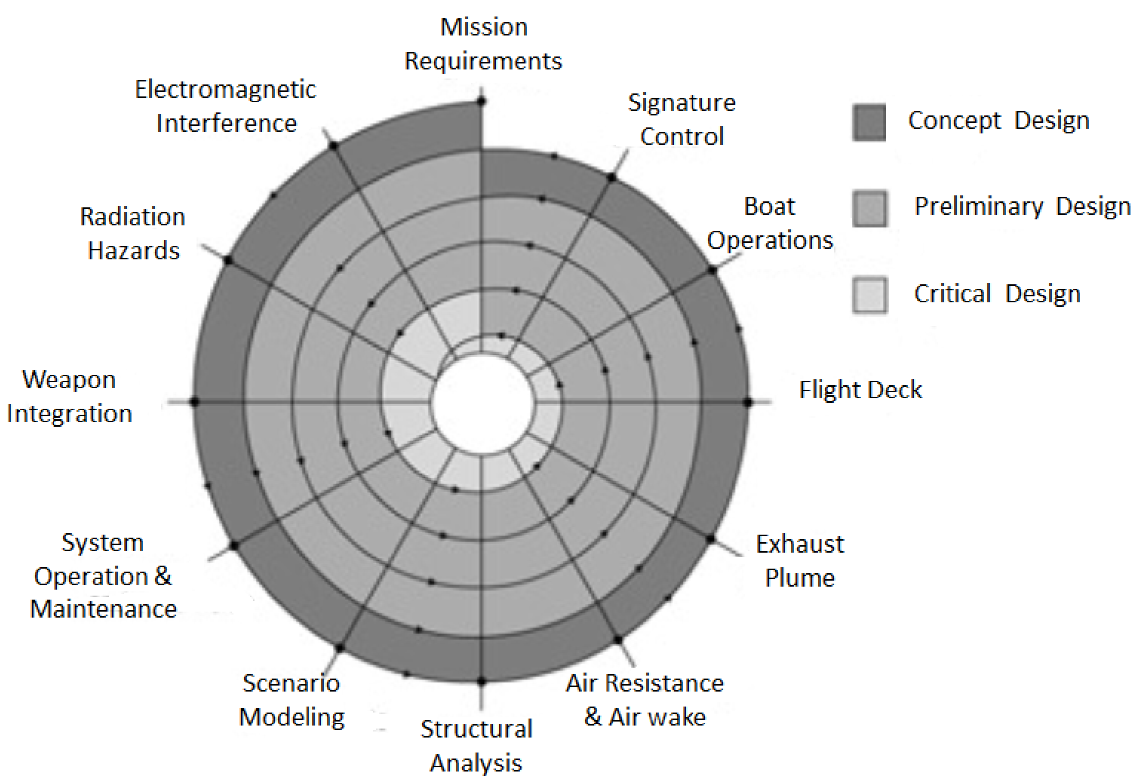
Lastly and most importantly, the overall ship design must be able to achieve an acceptable optimized performance of all the combat system and weaponry suites in order to meet the ship's operational requirements. The combat and weapon system are tested using factory acceptance testing (FAT) and are capable of meeting certain performance specifications (e.g., accuracy—probability of hit—and range of the gun, probability of detection, and tracking by radar/ESM) in specified environment conditions. These combat and weapon system are then aligned, installed, and integrated onboard the ship, as per suppliers' installation requirements. After the installation, integration, and check-out phase of all individual topside equipment, the vessel has to undergo harbor acceptance and an EMI/EMC trial. During the EMI/EMC trial, all the topside equipment is powered up, and all the EMI/EMC interaction issues are tested and verified. If during the CDR phase, the ITD study is not analyzed accurately and completely, then the performance of the topside equipment will not be maximized; and this might cause the vessel to be unable to meet its intended overall mission needs.

The author's recommendation is as follows: First, the topside designers can reference the Topside Design Consideration Checklist shown in Table 9 of Appendix D for designing the ship topside during conceptual/preliminary phase. Design assumptions and tolerances can be determined. Second, after CDR, the entire topside design must be verified using a traceability matrix to ensure that all the topside equipment's functionality and requirements have been fulfilled. Stakeholders must quickly resolve and approve all outstanding design issues.

C. SPIRAL MODEL FOR TOPSIDE DESIGN

The spiral model for topside design, as shown in Figure 5, is used to serve as guidance for topside designers. Topside designers should continuously refer to stakeholders' requirements to design the ship topside. The spiral model shows the key 11 topside design consideration branches, starting with EMI. The details of each branch translate into the Topside Design Consideration Checklist for the topside designers to work with the other disciplines. This spiral process is iterative throughout the design phases (e.g., PDR, CDR) and allows for earlier identification of potential problems in ship topside design. The process provides topside designers with the flexibility to investigate and analyze each individual design. The details of each individual branch are further explained in the next section.

Figure 5. Spiral Model for Topside Design



The Topside Design Considerations Checklist is referenced from Bayliss (2003) and is further improved by the author. This checklist is not the complete picture of all the topside design considerations but is definitely an adequate checklist and a good design practice for topside designers to use for conceptual naval ship design.

D. TOPSIDE DESIGN CONSIDERATIONS

1. *Electromagnetic Interference*. According to Transport Canada Civil Aviation (TCCA), electromagnetic interferences is "the phenomenon occurring when electromagnetic energy present in the intended operational environment interacts with the electrical or electronic equipment causing unacceptable or undesirable responses, malfunctions, interruptions, or degradations in its performance" (Transport Canada Civil Aviation [TCCA] 2008, 3). For all ship designs, EMI issues are topside designers' top priority and concern. Interference from one system can cause reduction in sensitivity and degradation of performance of another system when the two systems are used simultaneously. Backdoor EMI can also occur, where the electric field level generated by the source equipment exceeds the specified radiated susceptibility level of victim equipment. There is a risk that interference enters the victim equipment via ways other than the antenna (e.g., via cable penetrations or cables). This occurs mainly with non-military equipment, which has a lower susceptibility level than military equipment. In serious cases of interference, a non-transmit zone (NTZ) or modifications to the topside arrangement or equipment have to be made. All these interferences should be identified and recorded in the ITD analysis report.

In general, the ITD analysis identifies and mitigates the risk of interference and radiation hazards. The analysis results in a set of recommendations for (a) placement of all topside equipment, (b) NTZ, to prevent illumination of the main mast and radiation hazards, (c) blanking, (d) frequency management, (e) modification to the topside equipment (e.g., introducing and implementing filters for antennas to mitigate interactions); and (f) modifications to the vessel structures, if necessary (e.g., providing shielding structure/plates, introducing outriggers to increase antenna separation, being away from the walkway, and even reshaping the superstructure). The ITD analysis provides guidelines to end users concerning on-board radiation safety in the form of radar/antenna safe distance. Lastly, after CDR, there may be events that interference from or to the systems topside equipment cannot be resolved by placement, NTZ, blanking, or modifications to the vessel structure. Operational procedures for these systems are recommended by the topside designers and require approval from stakeholders.

For the ITD analysis report, the topside designers start off by collecting all the topside equipment specification data, especially the power, polarization, and frequency of the radiators, for their detailed analysis. They construct the frequency chart, source-victim matrix, and summaries in the ITD analysis. The frequency chart displays both transmit and receive frequencies of all the topside equipment. The source-victim matrix presents the expected level of interaction between each topside equipment pair. Many methods (e.g., Methods of Moment [MoMs], Finite Element Methods [FEMs]) analysis and software are available for the calculation of these interactions. The source-victim matrix interactions range from no interference, to backdoor EMI, to saturation, to damage of equipment. ITD analysis also recommends and proposes optimal locations for sensors (e.g., navigation radar, surveillance radar) and ESM to maximize the sensors' coverage, preferably a 360° field of view for the vessel. These locations have the least blockage/impact of other equipment (e.g., lights, outriggers, antennas) and ship structure. This is to optimize installed performance of sensors and their line of sight.

This thesis does not provide the formulas and calculations for the electromagnetic interference analysis. The focus of this thesis is to provide guidelines to topside designers regarding topside design considerations checklists to look out for during the design phase.

2. *Radiation Hazards (RADHAZ)*. RADHAZ describes the hazards of electromagnetic radiation to personnel (HERP), hazards of electromagnetic radiation to fuel (HERF), hazards of electromagnetic radiation to ordnance (HERO), and electronic hardware.

The safety of personnel working near high power transmitters onboard is critical. HERP is based on MIL-STD-464 (2010). Topside designers have to calculate the minimum safe distance for personnel with respect to all transmitting antennas based on the limit values stated in the standard. HERP applies for six minutes on the average and usually is calculated using an average transmitter power. Topside designers should ensure that there is no radiation hazard to personnel on normally accessible walkways, aircraft refueling areas, and RAS areas in the topside design. There should be markings or even paint on the topside for end-users to know the minimum safe distance for each transmitter. It is recommended that man-aloft switches be installed before the exits, and access points, to areas of transmitters. Areas protected by man-aloft switches would then be inherently safe with respect to the transmitters.

HERO is also based to MIL-STD-464 (2010). Topside designers should recommend to stakeholders that the chosen ordnance at least meet the MIL-STD-464 limit values. These values are the frequency-dependent minimum electric field values that the ordnance must be able to withstand. Most of the ordnance is able to withstand high electric field strength. In the event that the calculated electric field is higher than the ordnance-specific limits related to radiation hazards, repositioning the antenna is recommended. Topside designers should ensure that the designed/purchased ammunition lockers are metallic enclosures and that they are fitted with doors providing good isolation against an external electromagnetic environment. Operational procedures are recommended when handling the ammunition (e.g., nearby HF antennas should not be transmitting and should be switched off during the loading of ammunition).

HERF is based on the MIL-STD-464 (2010). The electric field strength at refueling points for the ship and aviation, RAS, VERTREP, and boat area are calculated and verified to be below the standard limit. The movement of fuel, stores, ammunition, and people must all be accounted for in the topside design. Not only are the keep-clear zones identified for RAS stations, but also the movement of the stores over the topside (usually by man or by small pallet vehicles) to the designated location on the ship must be considered.

Lastly, the transmissions of ship transmitters, especially the transmitting radars, may influence a helicopter on the helicopter deck or near the vessel. Topside designers should check that the end-user helicopter is compliant with MIL-STD-461, and also that the minimum safe distance from the transmitter to helicopter using peak transmit power is calculated. A detailed analysis regarding the helicopter approach and the choice of radar, together with operational procedures, should be carried out.

3. *Weapon Integration*. This subsection is divided in two: first, guns; second, missiles. They share some similarities in terms of topside design considerations (e.g., interaction with other projectiles) and the Blocking Assessment Model (BAM).

For the interaction with other projectiles, topside designers have to take note that the firing cones for the missiles/weapons do not overlap and thus pose no risk of ammunition collision. The design margin is included, and the repositioning of the weapons is recommended.

The BAM optical coverage plot provides a quick-check, line-of-sight view from the perspective of the antenna and weapon. In general, the BAM plot covers the full 360° in azimuth and below zero (horizon) to 90° in elevation. The topside designer will want to know how blockage from other systems and structure affect the antenna and weapon view. The topside designer can understand the combined field of view for the antenna and weapon in terms of bearings for all positive elevations from BAM. This will help the designer fine tune and optimize the location of antennas and weapons to obtain a broader firing arc for the weapon.

For gun topside design considerations, the top priority is weapon safety, followed by weapon coverage or arc of firing in terms of elevation and azimuth. There are mechanical/safety buffer stops designed for the guns to prevent them from firing towards the superstructure. The recommended weapon coverage is 360° for combined guns to provide protection and survivability for the vessel. The recommended surveillance radar coverage is also 360° to match with the guns' coverage. There may be requests from the end user to have depressed firing for the guns, especially for the ATTD, to tackle nearby firing. Using 3D modeling and gun installation requirements information, topside designers can determine the clearance space required. The other main design considerations are the blast pressure from the guns, which will affect the surrounding systems and equipment. If a system (e.g., communication or lighting equipment) is required to be placed near the vicinity of the guns, protection cases, shock mounts and militarized equipment are recommended. Blast Panels (port and starboard [stbd]) are recommended to be incorporated for the gun bay design for handling compartment overpressure. Firing the guns generates a lot of smoke content. It is advisable to place ventilation inlets and exhaust outlets away from the guns. For the gun foundation design, there are foundation frequency requirements. There is an increasing trend in the design of the main gun foundation to be integrated with the breakwater. It is V-shaped and facing forward, followed by a rectangular basin. The basin can also be used as a spent-case-ejection area. Topside designers should also take note of the gun maintenance required area (e.g., barrel swabbing area), which requires significant length. Beside the maintenance, the designs should also incorporate a sufficient ammo loading and handling area.

For the missile topside design considerations, the top priority is ammo safety. If missile launchers are placed near transmitters, especially high-powered HF transmitters, then the topside designer should first ensure that the electric field strength generated by the transmitter at the missile area remains lower than the missile susceptibility level. Next, recommendations (e.g., antenna blanking) should apply during missile launch so there will be no radiation hazards to a launched missile from onboard transmitters. Next, topside designers have to understand the firing clearance zones and debris ejection zones required and ensure that there is no blockage from the topside equipment/superstructure. Missile installation and embarkation space should be catered. Topside designers have to understand the missile efflux temperature and overpressure profile and thus ensure that the topside design is able to handle the high temperature and pressure to protect the ship structure and equipment (e.g., insert blast deflectors or open up ship-side openings for firing of missiles). There should be accessibility, concerning the loading and maintenance of the launcher. Firing missiles generates a lot of toxic gases, so it is advisable to place ventilation inlets and exhaust outlets away from the missiles. There is a high requirement for structural and foundational rigidity to meet missile installation. Last, a firefighting system should be installed for fire protection during the firing of a missile.

4. *System Operation and Maintenance Space.* As more ship designs are trending toward an integrated mast, arrangements for operation, maintenance, and access have to be taken into consideration. Topside designers should focus on the system installation requirements (e.g., embarkation route for the equipment, maintenance space, operating space, power, cooling, and safety requirements) of the system. They should consider

incorporating access to maintain/repair antennas, navigation lights, and other equipment fitted on the yard arms in their design. Using 3D modeling, the physical integration and checks of antennas with the structure should be considered to ensure that the operational movement of an antenna does not clash with the structure. Human factor ergonomics requirements should be considered and incorporated in the ship topside design.

5. *Scenario Modeling (Range-to-Target Model)*. During the development of a preliminary topside layout of a naval ship, alternative solutions should be evaluated against a scenario devised by the topside designer to inform and select the choice of payload configurations to meet the MOEs. It is possible to evaluate the design and obtain a comparative measure of how each solution would perform against a proposed threat scenario. Using probabilities of survivability of the vessel, it is possible to analyze a particular set of payload configurations against different attack/defense scenarios. This thesis uses the NPS Range-to-Target Model and back of envelope (BOE) for scenario modeling. This analysis requires parameters (e.g., the speed of the attacking/defensive missiles, the probability of kills from missiles/main gun, and the detection range of sensors). Further details are explained in Chapter V.

6. *Structural Analysis*. The ship topside structures (e.g., mast, deckhouse, platform) require continuous structural re-assessment for the introduction and/or removal of systems/equipment topside. The choices of material available for superstructure are mild steel, aluminum, and composite. There are advantages (e.g., high strength for steel) and disadvantages (e.g., less fire resistant for aluminum) for each material. Finite element analysis (FEA) modeling is required to understand the natural frequency stresses imparted in topside structures from design pressure. The mast frequencies should lie outside a +/- 20% band of significant excitation frequencies (e.g., main machinery and ship motions; Savage and Kimber 2010). Structural designers should analyze shock and vibration of the superstructure as part of the overall design of the ship. The topside and structural designers should analyze the pressure exerted on the superstructure during main gun firing. Software modeling and calculations can be first made during the design phase, and structural test firing checked during live fire trials. Last, there is also an increased interest in the protection/armor of the topside superstructure to reduce the

vulnerability of the ship. Modular armor plates are inserted at critical areas of the topside of the ship. There is research into ballistic protection technology (e.g., lightweight material for armor protection), which should facilitate the ease of implementation. Coating technology can also be applied to the surface of the mast/bridge/funnel structure to improve blast and fragmentation protection.

7. *Air Resistance and Air Wake*. Reshaping and resizing optimization of the mast/funnel on topside should be carried out to improve ship speed and movement. Air Flow analysis through the topside (mast) has also taken on increasing significance due to volume, temperature, and particulates from the exhaust into the topside and flight deck area. Wind tunnel test and computational fluid dynamics (CFD) software modeling can simulate various ship speeds and movements to understand the air flow so that the designers can better optimize the topside design. The size of the mast (slimmer mast) and funnel shape should be optimized for improved laminar air flow. There can be a significant increase in pilot workload due to the effect of laminar flow from the superstructure of the ship when he is trying to land his helicopter on the flight deck. Turbulence can affect the safety and operation of the helicopter (Savage and Kimber 2010).

8. *Exhaust Plume*. The toxic gas and high temperatures generated around the funnel are safety concerns to topside designers. Topside designers should note that the hot exhaust plume affects the antenna performance and so reposition the equipment away from the funnels. Several recommendations can be made, including reshaping the funnel, raising the height, and inserting expensive diffusers to reduce the amount of toxic gas flowing to the flight deck.

9. *Flight Deck*. The design of the flight deck depends heavily on the type of aircraft to be placed onboard, and also on the mission modules to be deployed. There are many design considerations for the flight deck:

- Operations of the helicopter, such as normal landing(aft/port), taking off, and emergency landing
- Operations of modular mission modules, such as deployment space, and securing of mission modules

- Operations of the personnel on flight deck, such as pilots, maintainers, and operators for either the helicopter or mission modules
- VERTREP operations
- Flight deck dimensions to suit all the above operations
- Flight deck safety net and deck marking
- Flight deck communications
- Flight deck drainage
- Water and gas refueling to hangar and flight deck
- Heli Visual Aids System (HELIVAS)
- Aircraft/helicopter and hangar securing system, such as the Aircraft Ship Integrated Secure and Traverse (ASIST) System
- Fire-fighting facilities
- Stowage facilities, such as aviation ammo storage and mission modules

The challenge for topside designers is not about just designing the flight deck based on these many inputs and considerations. They must also consider the other topside equipment working simultaneously and their impacts on the flight deck operation (e.g., will the transmitters affect the operation of the mission module?). At times, topside designers must also propose and present various combinations of operations that can be performed simultaneously on the flight deck and topside to the end-users.

10. *Boat Operations.* Boats of various kinds, including unmanned surface vehicles (USVs) must be deployed and recovered from off or through the topside. The deployment concepts for boats become uniquely assessed for each ship class, and the utility of deployment and recovery simulation are becoming very important to topside designers. One of the key topside considerations is the required boat davit crane operation clearance area. 3D modeling is recommended to simulate the movement of the crane, deployment, and recovery of boat/USV for integration checks.

11. *Signature Control*. The objective of signature control is to influence the onboard hit point location by reducing the susceptibility of the ship and as a result

increase its overall survivability. Shaping of the superstructure radiation improves the radar cross section (RCS) of the ship by deflecting the radiation emitted by the ship and not reflecting it back to the enemy's receivers. Radar absorbent material (RAM) helps absorb radiation emitted by the ship and reduces the radiation that the enemy receives. Innovative designs, such as a retractable integrated mast, are applied to reduce the RCS of the ship.

A hull cooling system is a cost-effective solution that uses seawater cooling to generate a water curtain to reduce infrared radiation emitted by the ship. Topside designers have to take note that the disadvantage of this hull cooling system is high wind, which can break the water curtain and make the ship detectable. Second, installing this system is not practical for covering the high mast. Third, the water screen masks a ship's own sensors. Another method is to apply low solar absorbance paint on the ship hull. One of the high infrared-red zones of the ship is the ship funnel; good heat insulation material can be used for the construction of the funnel.

There are other signature reduction control considerations (e.g., acoustic and magnetic). There are methods such as hull coating and machinery isolation to reduce the acoustic signature, and advanced degaussing to reduce the magnetic signature of the ship.

In summary, the reason for explaining the above 11 branches of the topside considerations is for topside designers to take note that, during the design phase, they might be so focused on one branch, such as optimizing the RCS for the superstructure or the placement of topside equipment, that they forget to check the interactions between the design branches and nearby topside systems. For example, the topside designer may propose a certain paint coating technology that is suitable for signature control, but he or she may miss out on the interaction of high temperature and pressure of the missile efflux on the paint coating. A topside designer not only has to look at the details of the design branches, but also needs to zoom out to see the big picture, including mission requirements and other interactions between systems to ensure a good topside design meet the MOEs.

E. TOPSIDE SIZING MODEL

The Topside Sizing Model is a heuristic design model based on rules of thumb and design experience. Heuristics work best when applied early to reduce the solution space (Maier and Rechtin 2002). The main objective of TSM is to explore the design space and allow for divergent thinking to generate more choices. There are a few design alternatives for the superstructure. The first design of a vessel has only one main block connected to the hangar block. The second design is one fwd block and one aft block connected to the hangar block. The aft block can be used for an aft stacked mast/funnel. The third design is one fwd block, one center block, and one hangar block with an aft stacked mast on top. TSM starts by initiating simple sizing for the superstructure block/blocks and trying to come out with a conceptual ship design. Next, TSM assists the ship designers in initial placement of all the major topside equipment with topside design considerations.

After sizing the superstructure and placement of topside equipment, the last space criteria condition has to be fulfilled. The superstructure, the topside equipment, and its additional required space must be lesser than the calculated length of the vessel previously derived from the Numerical Warship Design Procedure. These additional required spaces shall be catered for the various reasons:

- Sufficient space for adequate arcs of coverage for weapon and sensor suite
- Sufficient clearance space for blast pressure
- Sufficient clearance space for high temperature/plume
- Sufficient separation between radiating antennas
- Sufficient clearance space for helicopter for safe takeoff
- Sufficient operating envelopes of the ship crane
- Sufficient ammo loading and unloading for weapons and decoy
- Sufficient space for operation and maintenance of topside equipment
- Sufficient space for safety reasons
- Sufficient space for RADHAZ considerations

This issue was also highlighted in the description of the NFR 90 design (Schaffer and Kloehn 1991) where the length of 133 meters is a direct result of the spacing required on the topside. TSM does not optimize the length of the vessel but designs the initial topside layout and provides a feasibility physical check to ensure the topside equipment fits into the overall calculated length of vessel.

The designer has to understand and check the interactions and behaviors of the system and its surrounding systems because its performance may be impacted by and have an effect on the surrounding systems. Additional interaction space also needs to be provided. One example is the interaction of the SAM/SSM/Decoy systems near high radiating antenna.

If the space criteria is not fulfilled (e.g., if the length and beam is insufficient for the payload and superstructure layout), then there are three available options, as shown in Figure 6, for the designer to choose from in order to find a satisfactory conceptual ship design. The first option is to change the type and model of payload (e.g., find a smaller size payload). The second option is to change the payload space margin in the Numerical Warship Design Procedure. The third option is to change the design parameters with respect to (1) length proportion for front part of the ship forecastle, (2) length proportion for the superstructure block/blocks, or (3) length proportion of the hangar block

For this thesis, TSM is conducted within an Excel Model and is added on to the UCL Numerical Warship Design Procedure. The desired outcome is a satisfactory conceptual ship design. This model can also be added to the MIT Simplified Math Model for the Design of Naval Frigates.

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IV. DESIGN PHASE

A. OVERVIEW

The objective of this chapter is to develop and use the design methodology as displayed in Figure 6, which incorporates naval architecture and topside design considerations to design and come out with satisfactory conceptual frigate designs. The design of ship size has to meet the stakeholders' requirements, which are to fulfill the certain operational requirements of the vessel. The design of the ship size depends heavily on the payload configuration chosen onboard. Each payload has its own topside design considerations, thus affecting the overall dimensions of the vessel.

For example, in terms of anti-piracy or exclusive economic zone (EEZ) missions, the vessel has to achieve certain speed and range. It is required to be equipped with a surveillance radar to track its target and to be armed with armament, such as 76/30mm gun. It may also have helicopter/UAV capabilities to assist in its mission. The vessel has to be mission effective and perform its functions. Various system configurations are taken into account before the final decisions are made.

The design methodology consists of two phases. Phase 1 is to apply the UCL Numerical Warship Design Process (UCL, 1997) to derive the size, weight, and volume of the ship. The length, beam, and draft are obtained through iterations in order for the design to be balanced. The payload volume and weight data may be obtained from the existing database or is provided by the system suppliers. Main ship dimensions decide many of the ship characteristics for example stability, hold capacity, power requirement, and even economic efficiency.

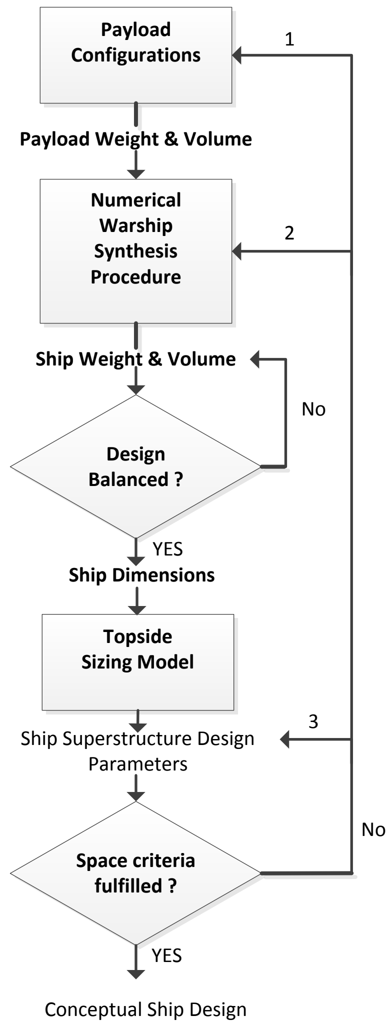
Phase 2, the Topside Sizing Model, starts once the design is balanced, ship dimensions are obtained, assumptions are made, and design parameters are inserted. The main purpose of this phase is to check whether the initial length and beam is sufficient to have an acceptable topside design after all the topside equipment being placed in the design. If there is insufficient length or beam, the design needs to be iterated using the three options, as stated in Chapter III.

B. BACKGROUND RESEARCH

A study was carried out on nine popular frigate designs, such as La Fayette (France), Valour (South Africa), and Sachsen Class (Germany) to understand their design parameters, especially with respect to the length displacement ratio and beam draft ratio. The results are shown in Appendix E. The findings for the length displacement ratio averages 3.34, at while the beam draft ratio averages at 7.32. This is comparable to the values used in the UCL Numerical Warship Design Procedure.

The second purpose is to understand the topside layout and commonality of these ten frigates. The findings for the commonality in these ship designs consist of forward block (inclusive of forward stacked mast), aft block (can be either used for aft stacked mast or funnel), and hangar block. This type of layout design with forward and aft block has several advantages. First, it improves EMI/EMC by allowing greater antenna separation. Second, it increases survivability and is better able handle threats and allow for design redundancy.

Figure 6. Design Methodology for Conceptual Ship Design



C. NUMERICAL WARSHIP DESIGN PROCEDURE

The payload configuration of the multi-role stealth frigate includes the baseline payload configuration, main sensors (ESM), surveillance radar and FCR, weaponry (SAM, SSM, main gun, and ATTD), countermeasures, aviation capacity (helicopter), and mission modules (UAV, USV, and unmanned underwater vehicle [UUV]). This payload configuration is selected to meet functional requirements and missions capabilities, as stated by stakeholders. The Numerical Warship Design Procedure is conducted within an Excel model.

The parameters used for the Numerical Warship Design Procedure (UCL, 1997) are as shown in Table 2.

Table 2. Parameters Used in the Numerical Warship Design Procedure

Payload Volume Fraction	0.2	
Length Displacement Ratio	7.5	
Beam Draft Ratio	3.25	
Block Coefficient	0.5	
Waterplane Coefficient	0.75	
Deck Head Height	3	m
Scaling Factor for Length	15%	
Scaling Factor for Beam	14%	

From University College of London (UCL), Naval Architecture M.Sc Ship Design Procedure and Data Book, London: Naval Architecture Research Group, Department of Mechanical, University College London, 1997.

The design is balanced on two conditions:

Displacement = Weight of the groups

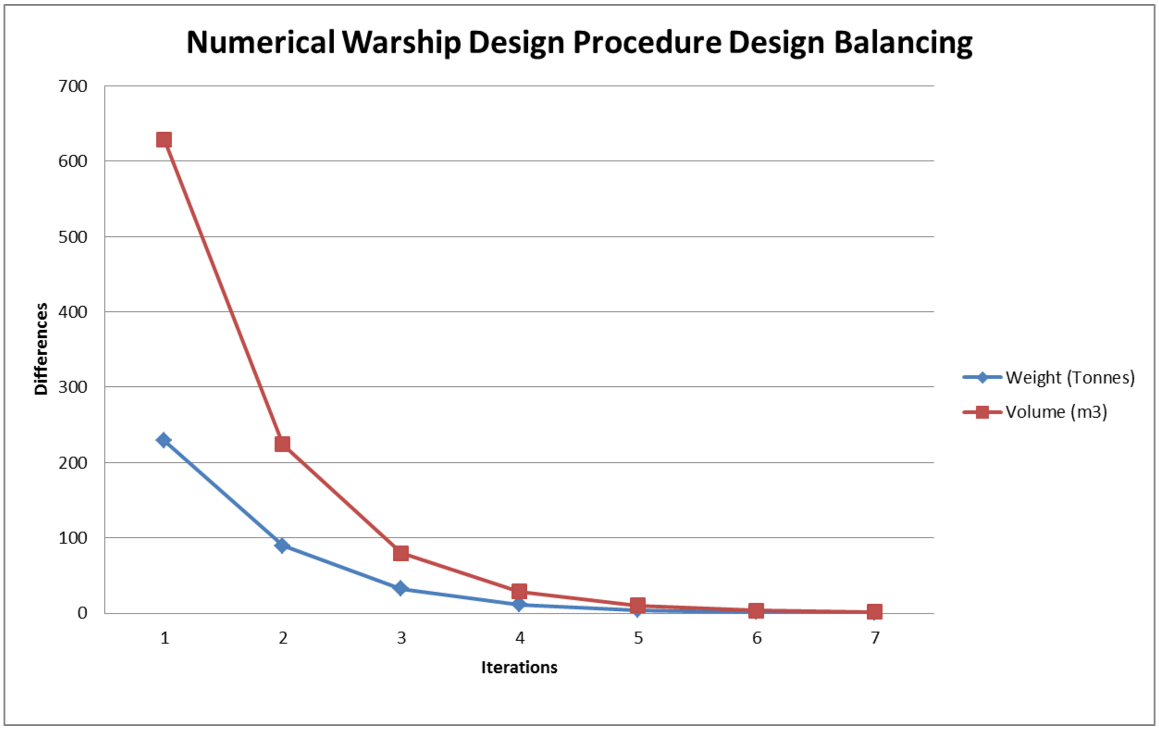
Volume available in the hull ≥ volume required by the groups

Based on the baseline payload configuration shown in Table 8 of Appendix C, and after seven iterations as shown in Figure 7, the results are as shown in Table 3.

Table 3. Results of Baseline Configuration

Total Payload Weight	137.7	tonnes
Total Payload Volume	2670	m^3
Ship Weight	3740	tonnes
Ship Volume	12204	m^3
Waterline Length (LWL)	110.2	m
Length Overall (LOA)	126.7	m
Beam Overall (BOA)	15.6	m
Draft	4.21	m

Figure 7. Design Methodology for Conceptual Ship Design



After phase 1 is completed (the design is balanced), several parameters (such as length, beam, and draft) of the ship are obtained. The dimension of a ship should be coordinated such that the ship satisfies the design conditions. The ship should not be designed larger than truly required or necessary. The main reasons are wastage, low speed, increased power requirements, and increased cost.

D. TOPSIDE SIZING MODEL ANALYSIS

In phase 2, several assumptions are made in the Topside Sizing Model:

1. The hull form of the frigate is based on a monohull design. The stakeholders' preference for the superstructure design is to have one fwd block, one aft block connected to the hangar block for better EMI/EMC performance, and higher survivability. The main gun (center [C]), decoys (port/stbd), one ATTD(C), and SAM(C) is preferably installed in front of the fwd block. SSM (one facing port and one facing stbd) and torpedo launcher (port/stbd) is installed between fwd and aft block. A helicopter can be secured on the helideck or stored inside the hangar.

2. The usable space at the front of the ship for topside equipment is limited especially for the main gun on deck and gunbay (1st deck). Based on frigate design examples, as shown in Appendix E, the unusable space is approximated 0.050–0.080 proportion of the LOA.

3. Beside the actual equipment space, there is a need for additional required space by the payload to be catered (e.g., operation, maintenance, blast zone, clearance zone, firing angle, ammunition loading of equipment, safety requirement, RADHAZ, and class rules). These additional required spaces can be inferred from data inside the equipment installation document and through design experience.

4. Based on the frigate design examples shown in Appendix E, the fwd block length is approximated 0.12–0.17 of LOA, and aft block length is approximated 0.09–0.13 of LOA.

5. There shall be one hangar designed for storing the helicopter.

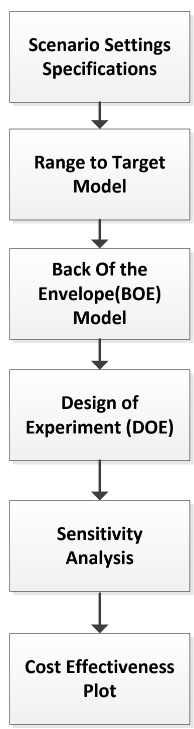
Sensitivity analysis can be applied to TSM in terms of varying the length proportion for each superstructure block and hangar block to generate more and practical superstructure designs. The result shows that the frigate of a ship design in Figure 24, with its baseline payload configuration as shown in Table 8 of Appendix C, is able to meet TSM space criteria with the design parameters as shown in Tables 10 and 11 of Appendix F. The results also show a 6.92m buffer length, which can be used for a superstructure block size upgrade, placement of more topside equipment, and future growth purposes. The sensitivity results of other alternative designs are shown in Appendix H.

V. COST-CAPABILITY ANALYSIS

A. BACKGROUND

Cost-capability analysis (Boensel 2015) is applied to examine the trade-off in the capability of a system versus the vessel cost of procurement. Its objective is to recommend to the stakeholders a certain size of frigate with the type of payload configuration that fulfills their effective needs and meets the MOE. However, given the size of the naval fleet and the budget constraints, this has to be done cost effectively. The intent of this analysis is to identify the most cost-effective way to improve the defensive capability of naval fleets against swarm missile/UAV attacks. An improvement, such as upgraded missile guidance systems or the addition of an ATTD, would enhance the ships ability to defend and engage the swarm missiles/UAVs. An overview of the cost-capability analysis is displayed in Figure 8.

Figure 8. Overview of Cost-Capability Analysis



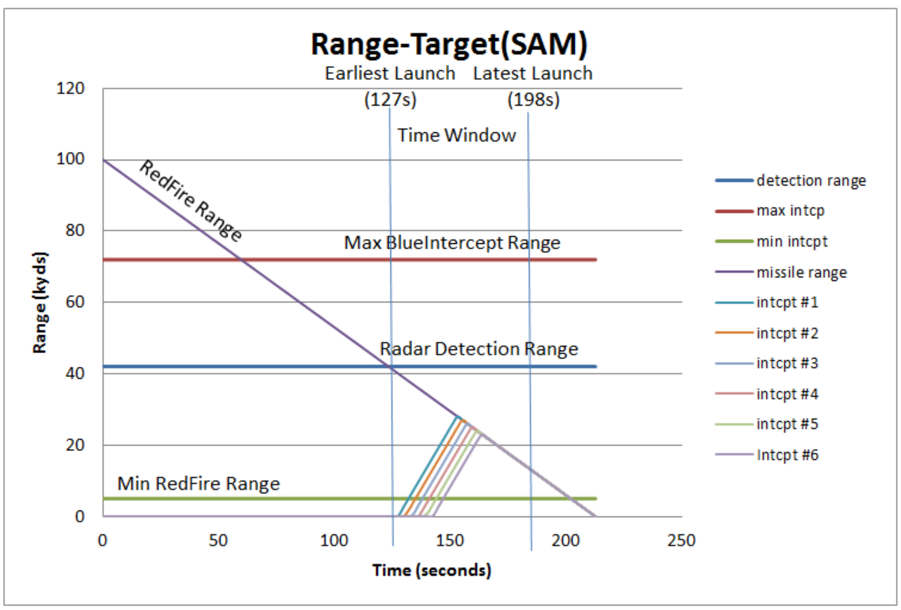
B. COST-CAPABILITY MODELS ANALYSIS AND RESULTS

The capability analysis starts off with the scenario-settings specification, as listed in Appendix A. The analysis is then followed by the range-to-target model (Boensel 2015) and back of envelope (BOE) model analysis (Boensel 2015) using an Excel model. The BOE analysis provides efficient and fast validation and verification of results. The BOE fleet defense model is a stochastic model for the operational scenario.

1. Range-to-Target Model

The purpose of the range-to-target model is to determine the maximum number of missiles that could be fired from each ship at the incoming RedFire missiles. The range-to-target graph (BlueIntercept vs. RedFire) was generated to show the relationship between detection range, time between launches, missile range, and minimum and maximum interception range at various distances and interception times, as displayed in Figure 9.

Figure 9. Range-to-Target Plot (BlueIntercept Missile vs. RedFire)



As shown in Figure 9, there is a range gap of 30 kyds between missile interception capability and sensor detection capability. Because the missile interception range is not fully utilized, the time to react to incoming threats is limited by its detection range. Coupled with launcher process time and time between launches, this results in only 24 BlueIntercept missile launches within the time window of 75s from detection of incoming missiles. The earliest first launch was at 127s after first detection at 123s.

$$t_0 = \frac{(initial\ range - detection\ range)}{missile\ velocity} = \frac{100-42}{0.47} = 123s \quad (1)$$

The above reasons contribute to a high number of frigates and AWS not able to defend themselves against incoming threats and being sunk.

The range-to-target graph (main gun vs. BlueIntercept Leakers) was generated to show the relationship of ATTD engagement range (16 kyds) and time between main gun intercepts and missile range, Figure 10. From this graph, it can be seen that the main gun system of a frigate has only twelve chances of engagement before the RedFire missile hits the ship.

The range-to-target graph (ATTD vs. BlueIntercept Leakers) was generated to show the relationship of ATTD engagement range (3 kyds) and time between ATTD intercepts and missile range, Figure 11. From this graph, it can be seen that the ATTD has only three chances of engagement before the RedFire missile hits the ship.

Figure 10. Range-to-Target Plot (Main Gun System vs. RedFire)

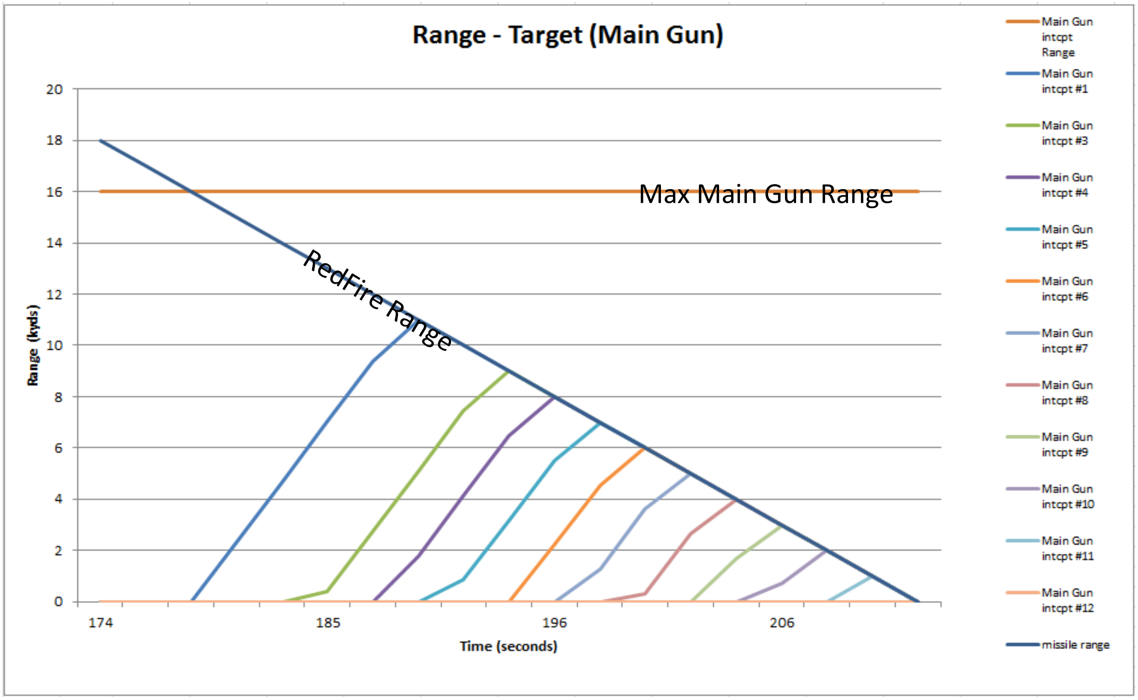
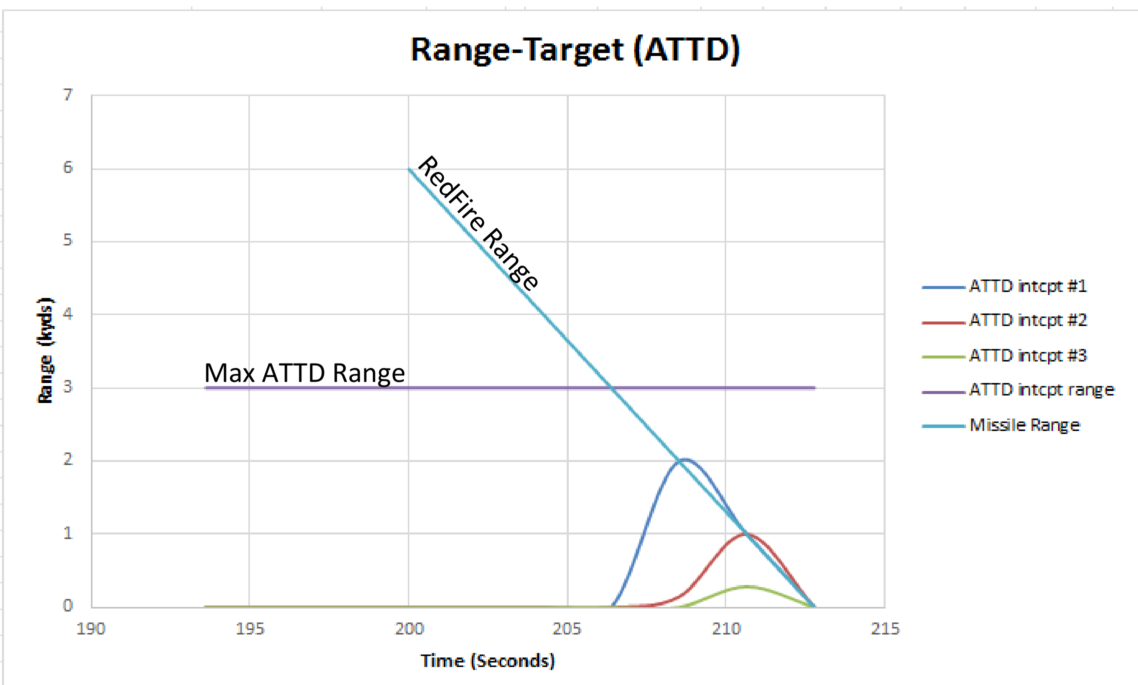


Figure 11. Range-to-Target Plot (ATTD System vs. RedFire)



2. Back of Envelope Model

The BOE model (Boensel 2015) was created with the following engagement assumptions:

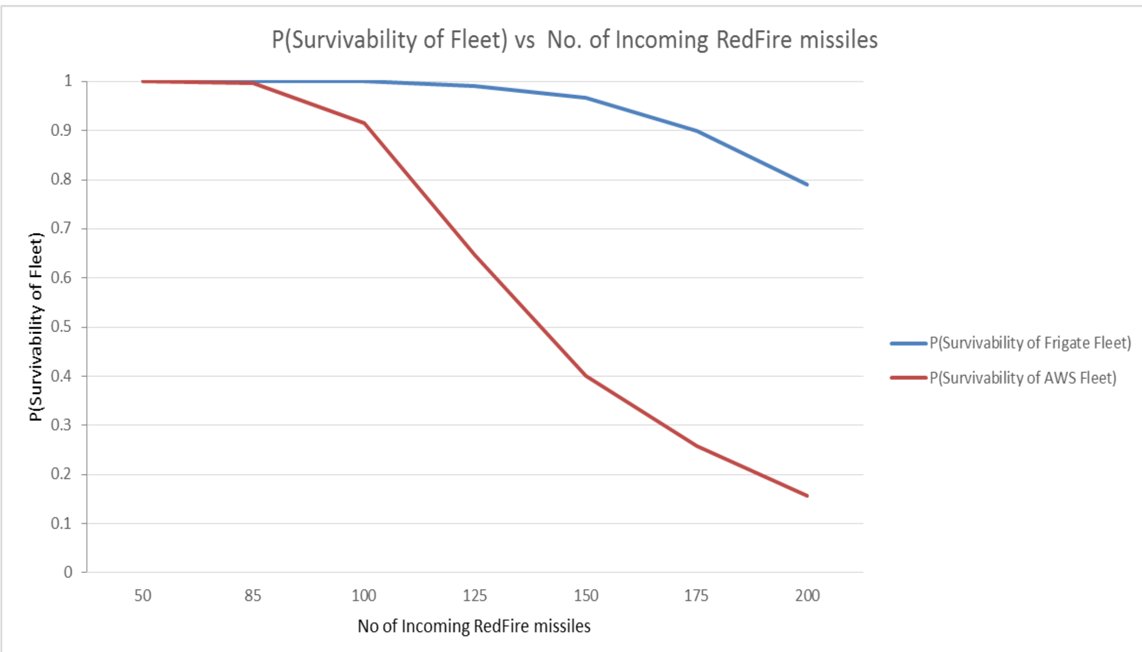
- The navy fleet (frigate and AWS) is treated as a point target.
- At one time, the incoming RedFire missiles should be treated as one batch of 200 missiles and not sequential. The ship can detect and track up to 250 RedFire missiles simultaneously.
- Given the high number of incoming RedFire missiles, one ATTD gun is fired at one target each time to increase the overall number of missile engagements.
- Unlike BlueIntercept missiles, which can engage any missiles that are detected, the ATTD can only be employed to engage targets that are directed towards the ship on which the ATTD system is deployed (i.e., ATTD on one frigate cannot be used to engage targets that are directed towards another frigate or AWS).

The BOE models were created using the attributes of the defense capabilities listed in Appendix A, and the results are shown below.

For scenario 1, results from the range-to-target analysis suggest that only 24 BlueIntercept missiles can be launched from the single frigate within the interception window. The BlueIntercept missiles (first-layer defense) of the frigate is capable of intercepting approximately 17 missiles, while the main gun (second-layer defense) hit approximately five missiles. The countermeasure is activated and able to attract four missiles, while the ATTD is able to hit approximately two missiles. The statistical data generated showed a probability of 0.382 in sinking the frigate by a salvo of 50 RedFire incoming missiles from first 500 simulation runs.

For scenario 2, results from the range-to-target analysis suggest that only 24 BlueIntercept missiles can be launched from each frigate within the interception window. Thus, a total of approximately 122 BlueIntercept missiles are fired from the frigates to counter the salvo of 200 RedFire missiles. An approximated 85 RedFire missiles are intercepted, but around 69 leakers fly towards the AWS and 46 leakers target the frigates. The number of BlueIntercept missiles fired is limited by detection range, the time interval between launches, and the speed of its missiles. The statistical data generated from first 500 simulation runs showed a survivability of 79.6% for the five frigates and a survivability of 14.9% for the four AWS. In the case of 50 incoming RedFire missiles, as shown in Figure 12, none of the RedFire missiles is expected to breach the fleet defense. If there are more than 85 incoming RedFire missiles, then there will be at least one AWS sunk. If there are more than 100 incoming RedFire, then there will be at least one frigate sunk. Hence, the current fleet AAW capability with the baseline configuration is capable of defending against approximately 80 incoming RedFire missiles, and no ships are sunk.

Figure 12. Probability of Survivability of Fleet (5 Frigate + 4 AWS) vs. No Incoming RedFire Missiles



Overall, the results from the two scenarios above illustrate that the current fleet AAW payload configuration is insufficient to provide adequate air defense for frigates and AWS in an operational scenario.

3. Design of the Experiments Model

In order to determine the cost-effective set of improvements to either the sensors, BlueIntercept missiles, main gun, countermeasures, or the ATTD, a design of experiments (DOE) is used. A DOE serves as the primary tool to identify and shortlist the parameters that yield the best possible outcomes in meeting the objectives. The purpose of a DOE is to investigate and identify possible parameter changes that will significantly improve the outcome (i.e., reduce the chance of the frigate and AWS being sunk).

Minitab software is used to generate a series of combinations for input to the DOE model. The output from the number of frigates and AWS sunk for each combination is used on Minitab to process and generate the interactions of the parameters/factors with the outcome. Using Minitab, factorial analysis was performed to determine the impact of the various defense attributes on the performance of the overall defense (average number of leakers that target the AWSs per run). This allowed for the identification of attributes that have higher leverage on performance. The series of combination of inputs and outputs for the two scenarios are displayed in Tables 12 and 13 of Appendix G. For scenario 1, the results of the factorial analysis are captured in the main effects plot in Figure 13 and pareto plot in Figure 14. For scenario 2, the results of the factorial analysis are captured in the main effects plot in Figure 15 and pareto plot in Figure 16. The design parameters are 1/32 fraction, 64 runs, and resolution V $2^{\wedge(11-5)}$.

Figure 13. Main Effects Plot for 11 Parameters (Scenario 1)

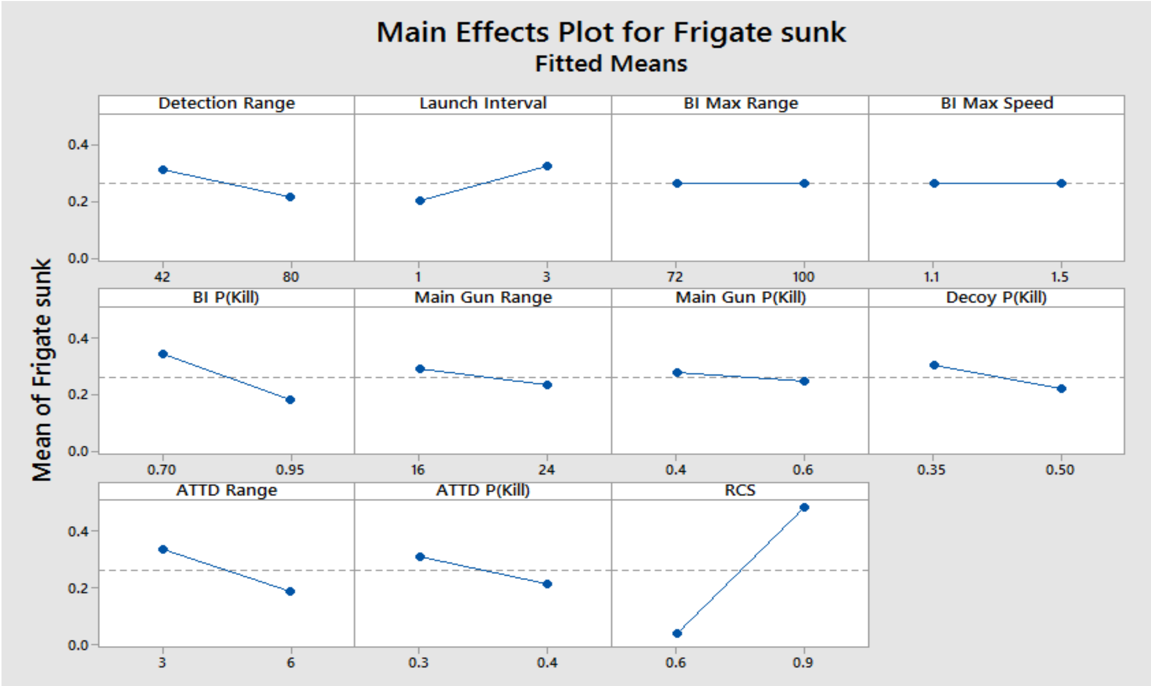


Figure 14. Pareto Plot for 11 Parameters (Scenario 1)

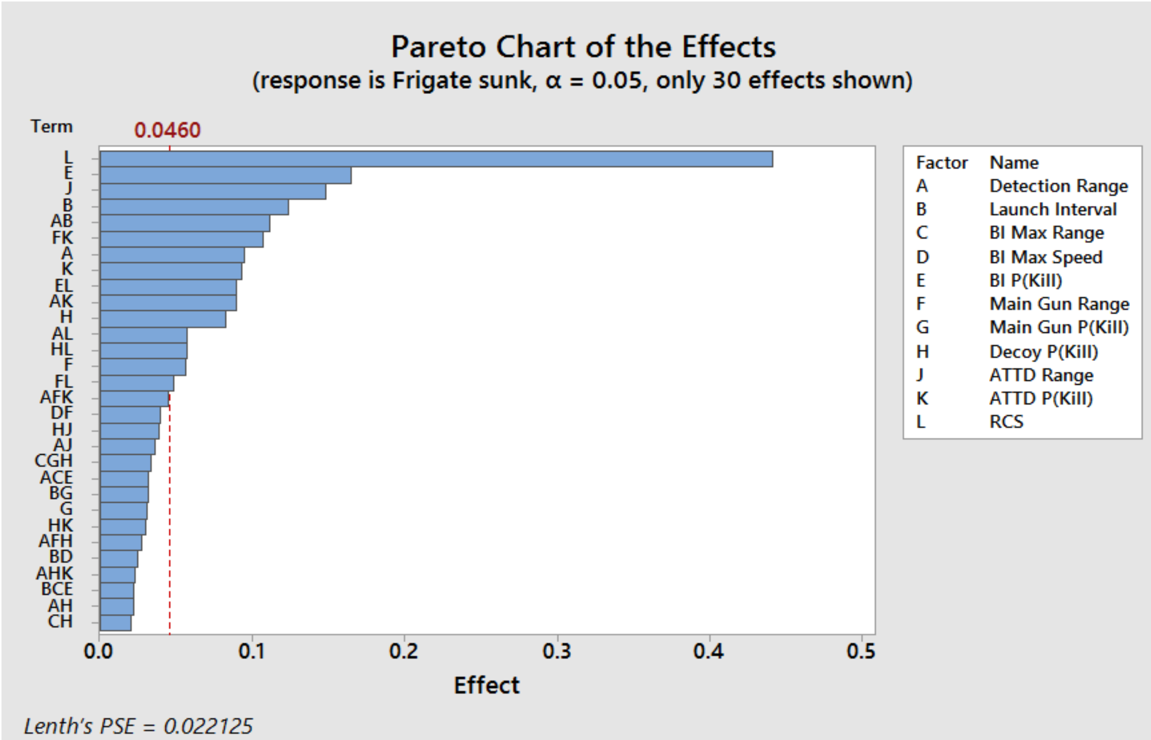


Figure 15. Main Effects Plot for 11 Parameters (Scenario 2)

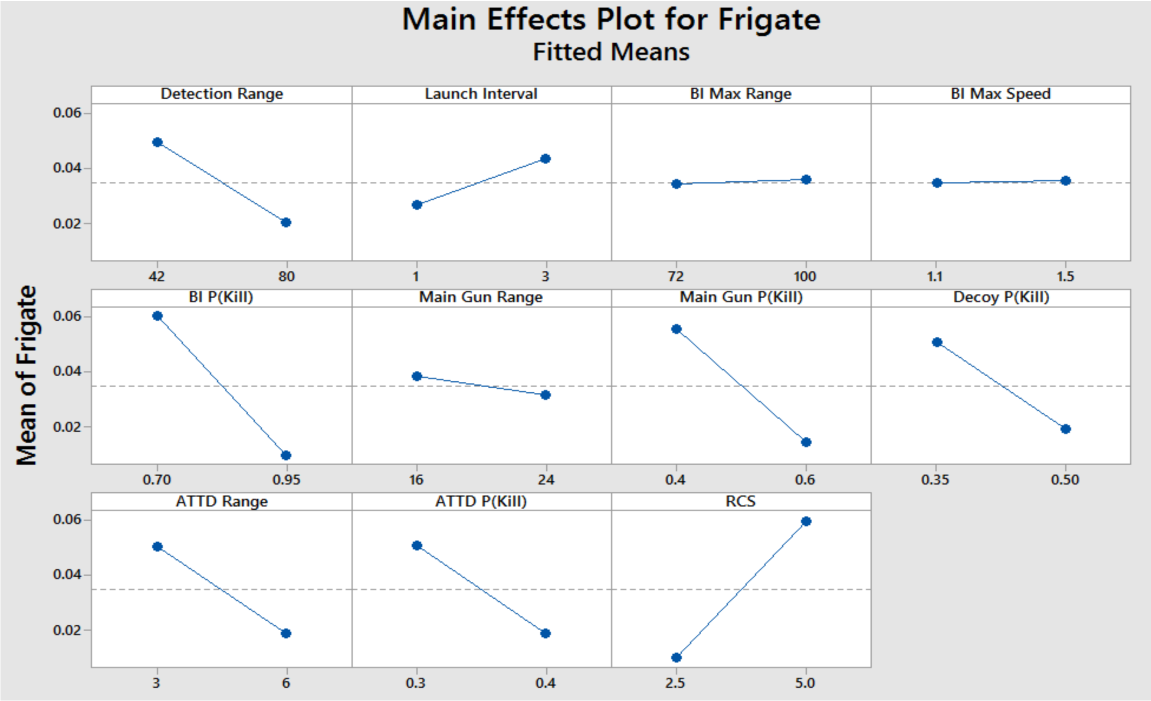
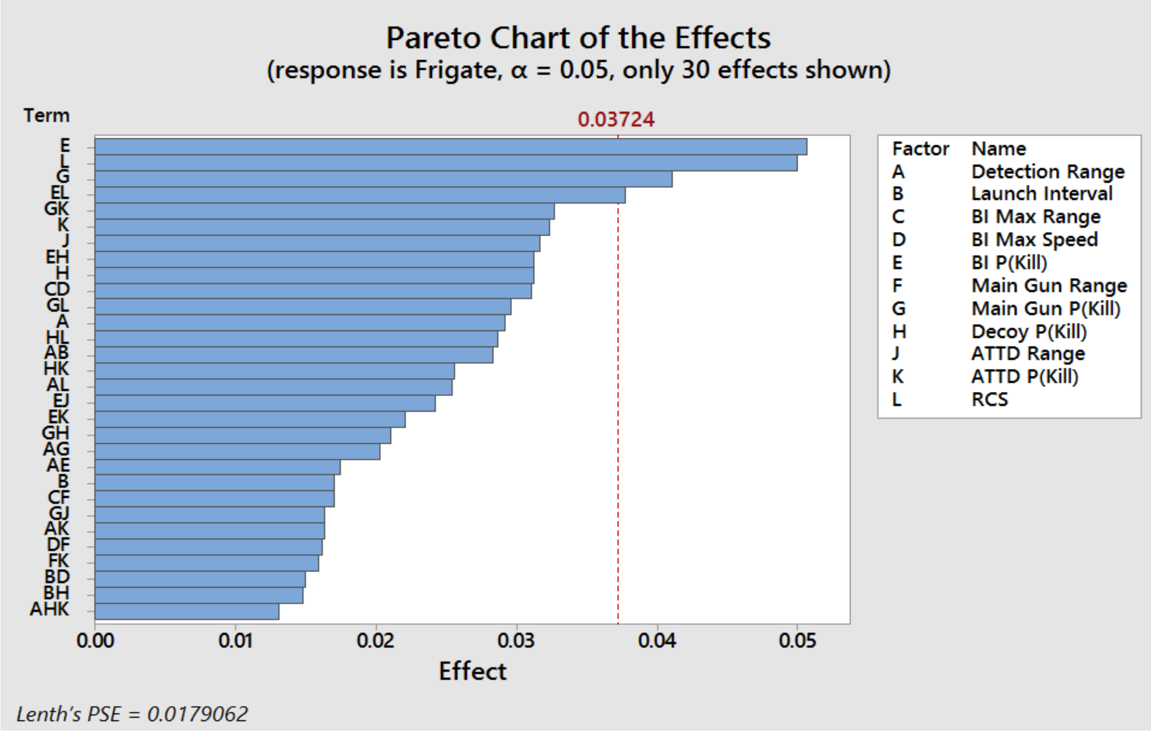


Figure 16. Pareto Plot for 11 Parameters (Scenario 2)



The degree of contribution by each of the attributes in a Main Effects Plot is indicated by its slope; the steeper the slope, the greater the contribution to the performance. A comparison check for the significant attributes between the single and escort scenario is performed. A summary table of common higher significant attributes for sensitivity analysis is displayed in Table 4.

Table 4. Summary of Attributes for Consideration

Attributes	Rank
BI P(Kill)	1
RCS	2
Main Gun P(Kill)	3
ATTD P(Kill)	4
ATTD Range	5
Decoy P(Kill)	6
Detection Range	7
Launch Interval	8

The main effects plots and pareto plot showed that both BI P(Kill) and RCS have the most significant impact on the frigate sunk, followed by main gun P(Kill) and ATTD P(Kill). This goes well with the BOE analysis, which suggests that if the probability of kill by the BlueIntercept missiles is enhanced, then more BlueIntercept missiles can be fired to intercept the RedFire missiles, thus enhancing the survivability of the AWS ship.

4. Sensitivity Analysis

Following the DOE analysis, a sensitivity analysis of the parameters with higher significance was performed. There is better granularity in parameter settings obtained from the DOE, and this will provide finer resolution on the outcome effects, which are the survivability of the frigate and AWS. This process facilitates the stakeholders in their final decision making on the optimal cost-effective solution.

The sensitivity analysis is done incrementally based on the matrix, as displayed in the Table 5. A total of 41 options are generated, and these options provide different upgrade combinations, each with varying levels of performance. The specific upgrades and the exact performance for each of these options and parameters used, as shown in Table 14, are captured in Appendix H. It should be noted that these options were conceived based on the following assumptions:

a. The missile inventory of each frigate cannot be increased further, leaving a maximum of 32 missiles per frigate.

b. The probability of BlueIntercept missiles can be improved though acquiring a more advanced missile system that has better guidance, propulsion system, and control mechanisms.

c. RCS can be improved by shaping the superstructure and adopting an RCS design approach for the vessel.

d. Main gun P(Kill) can be improved through bigger caliber, smart ammunition, and turrets.

e. The probability of ATTD intercept and range can be improved through barrel size, rate of firing, smart ammunition, and radar tracking.

f. Decoy P(Kill) can be improved in software algorithm, ammunition type, and the number of rounds.

g. Sensor detection range can be improved by upgrading and using better radar technology. Upgrading can be related to replacement with more powerful and larger transceivers.

h. The launch-time interval is affected by the Combat Management System (CMS) and Missile Launch System (MLS). These can be improved by upgrading or changing the MLS electronics and CMS electronics.

However, the stakeholders and designers need to keep in mind that any upgrades to the payload configuration will result in a larger ship, higher weight, and higher cost to the overall ship weight budget and cost calculation.

Table 5. Matrix for Sensitivity Analysis

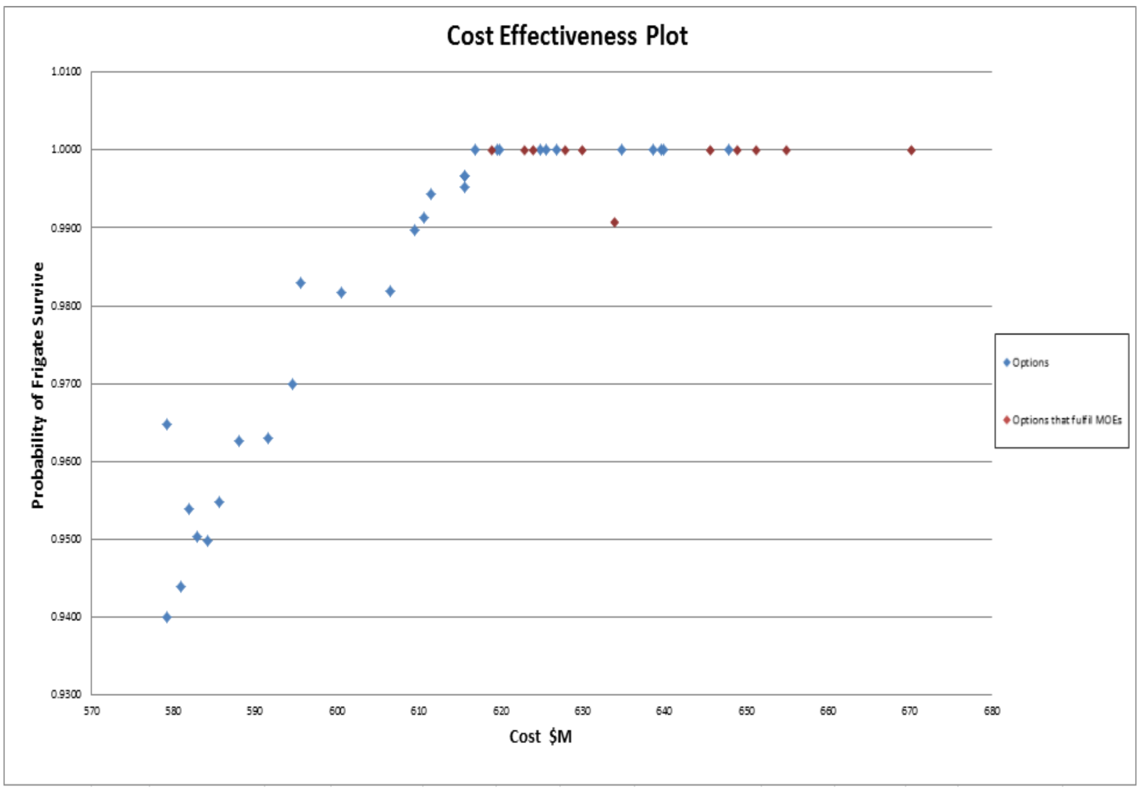
		Attributes								
		BI P(Kill) (1)	RCS (2)	Main Gun P(Kill) (3)	ATTD P(Kill) (4)	ATTD Range (5)	Decoy (6)	Detection Range(7)	Launch Interval (8)	Install 3rd ATTD (9)
Standalone	Option 1	x								
	Option 2		x							
	Option 3			x						
	Option 4				x					
	Option 5					x				
	Option 6						x			
	Option 7							x		
	Option 8								x	
Missile Centric	Option 9	x	x							
	Option 10	x		x						
	Option 11	x			x					
	Option 12	x	x	x						
	Option 13	x	x		x					
	Option 14	x	x					x		
	Option 15	x	x	x	x					
	Option 16	x	x	x		x				
	Option 17	x	x	x	x	x				
	Option 18	x	x	x	x	x		x		
	Option 19	x	x	x	x	x	x	x		
	Option 20	x	x		x	x				
RCS Centric	Option 21		x		x	x				
	Option 22		x	x	x	x				
	Option 23		x	x	x	x				x
	Option 24		x	x	x	x				x
	Option 25		x		x	x				x
	Option 26		x		x	x				x
Main Gun Centric	Option 27			x	x	x				
	Option 28			x	x	x	x			
	Option 29			x	x	x		x		
	Option 30			x	x	x				x
	Option 31			x	x	x				x
ATTD Centric	Option 32				x	x	x			
	Option 33				x	x		x		
	Option 34				x	x		x		
	Option 35				x	x				x
	Option 36				x	x				x
CMS Centric	Option 37	x							x	
	Option 38	x	x						x	
	Option 39	x	x	x					x	
	Option 40	x	x	x	x	x			x	
	Option 41	x	x	x	x	x			x	

From the results obtained in Table 15 of Appendix H, in order to achieve both the MOE, which is 90% confidence of a more than 99% chance of surviving for the frigates, and 90% confidence of a more than 99% chance of surviving for the AWS from a salvo of 200 RedFire Missiles fired to have simultaneous arrival in the vicinity of the ships, only Options 20, 23, 24, 25, 29, 30, 31, 33, 34, 35, 36, 41 would meet this requirement.

5. Cost-Effectiveness Plot

The assessment of the analysis is completed with cost-effectiveness considerations. This is to obtain the most cost-effective way to improve the overall capability of the frigate. Using the results in Table 16 of Appendix I, a cost-effectiveness plot, as shown in Figure 17, was constructed to evaluate the cost-effectiveness.

Figure 17. Cost-Effectiveness Plot



From the plot, Option 34, the baseline payload configuration with the only an upgrade to surveillance radar model 2 (higher sensor detection range) and to ATTD model 3 (higher probability of kill at 0.8 and range at 12 kyds), is the recommended solution. This option fulfilled the MOEs at the lowest cost of $618.925M per frigate. At times, the recommended solution may not be available due to technology constraints, if the electronic system or weaponry is unavailable for sale, for export reasons, or for political reasons. Thus, the cost-effectiveness plot is useful in the sense that it also provides to the stakeholders the other available options that meet all the MOEs, but at a higher price.

VI. CONCLUSION AND RECOMMENDATIONS

At times during designing naval ships, ship designers lose sight of the overall big picture, functionalities, and the mission needs of the vessel. Moreover, naval architects concentrate on the speed, range, and displacement and ship stability calculation. Topside designers are more concerned with the placement, feasibility checks, and optimization of the location of both the topside combat systems and platform systems. Ship designers are designing in “silos,” and thus the design of the ship is not well integrated. At the conceptual and tender phase, ship designers can apply a systems engineering approach for the preliminary design of a frigate. Ship designers can be brought together to understand the big picture and work towards a common set of functions and requirements. They are able to apply Numerical Warship Design Procedure together with the Topside Sizing Model to quickly determine the ship’s parameters and achieve satisfactory conceptual ship designs. Of course, the overall design of the ship will still need to look into other analyses (e.g., stability, speed, and power analyses).

The synthesis process continues to find alternative solutions and finally derive a cost-effective design solution. From the results of the BOE simulation, it can be seen that the existing defense payload configuration is insufficient to protect the five frigates and four AWS from a swarm of 200 missiles. The design of experiments results suggests that the kill probability of the BlueIntercept missile and RCS have a significant impact in defending and protecting the frigates and AWS in surviving the swarm attack of the RedFire missiles. After examining the cost-effectiveness plot, several viable options are generated. It is recommended that the detection range of surveillance radar and the ATTD be upgraded. This would enable the fleet to survive the swarm of RedFire missile attacks. Hence, this simulation result would allow the defending fleet to design its payload configuration to handle such threats.

The recommendations are for further enhancements that can be added in the topside sizing model to look into sizing of the height of the superstructure. This will provide more details to the topside consideration studies and overall shaping of the superstructure. If time and budget permits, the overall ship design should include the detailed internal layout for feasibility check and a preliminary EMI/EMC analysis study.

As for the cost-capability analysis, more scenarios and modeling can be performed to ensure a more robust solution (e.g., an offense scenario for the fleet of frigates in littoral environment). Secondly, more MOEs, such as radar detection capability, lethality of the missiles and ammo, and first strike capability, can be added to the scenarios and models to provide more detailed assessments.

APPENDIX A. SCENARIO DEVELOPMENT

The scenario settings are referenced from NPS Capability Engineering. The two scenario settings identified for this thesis are as follows:

1) Swarm missile attack versus single frigate

2) Escort mission (swarm missile attack versus a force of four amphibious warfare ships [AWS] and five frigates)

Scenario 1. Details of the first scenario setting (swarm missile attack versus single frigate) are as shown here:

A frigate is attacked by a near-simultaneous launch of 50 surface-skimming, anti-ship cruise missiles.

The incoming missiles (RedFire) can be detected by a ship's surveillance radar at a maximum range of 42 kyds. The time to detect and classify a target for the expected sea state is lognormally distributed with a mean of 4 seconds and a standard deviation of 2 seconds. The frigate has a combat management system and can simultaneously track and classify up to 50 incoming missiles.

The frigate is armed with BlueIntercept (BI) surface-to-air missiles (SAM; model 1). They are fired sequentially at a minimum interval of 3 seconds per missile. The BlueIntercept missiles fly at a speed of 1.1 kyds per second. Each BlueIntercept missile has a 0.70 probability of kill against a RedFire missile. The BlueIntercept missile has a maximum range of 72 kyds and a minimum range of 5 kyds (engagement inside 5 kyds is not possible due to safety stand-off).

The frigate is armed with 32 BlueIntercept missiles.

The RedFire missile flies at about Mach 1.25 (standard day, about 0.47 kyds per second) and is launched from a point at least 100 kyds from the frigate

Each RedFire has a probability of hitting one of the ships at the force of 0.80, and, given a hit, a probability of sinking the frigate = 0.30

The RedFire missile uses a radar-seeker head and has a high probability 0.90 of hitting a larger target with a large RCS. A reduction in RCS of the frigate will result in a lower probability of being detected and hit.

If a RedFire closes within 16 kyds of frigate, then it can also be engaged by the ship's main gun system (model 1). The ship's main gun system has a 0.4 probability of killing an inbound RedFire. There is one main gun per frigate in the force. The total time for a full main gun engagement is 3 seconds (acquire, track, fire).

If RedFire closes within 10 kyds of the frigate, then the decoy rounds of the frigate are activated. The decoy (model 1) has a 0.35 probability of attracting an inbound RedFire.

If a RedFire closes within 3 kyds of frigate, then it can also be engaged by an Area Terminal Type Defense (ATTD) system (model 1). A single ATTD system has a 0.3 probability of killing an inbound RedFire. There are two ATTD onboard the frigate in the force. The total time for a full ATTD engagement is 2 seconds (acquire, track, fire).

Scenario 2. Details of the second scenario setting (Escort Mission: swarm missile attack versus a force of four AWS and five frigates) are as shown here:

A force of four AWS transporting high valued items protected by five frigates is attacked by a near-simultaneous launch of 200 surface skimming anti-ship cruise missiles. The defense capability of the AWS consists of only the ATTD.

The incoming missiles (RedFire) can be detected by frigate surveillance radar model 1 at a maximum range of 42 kyds. The time to detect and classify a target for the expected sea state is lognormally distributed with a mean of 4 seconds and a standard deviation of 2 seconds. The five frigates share a common combat management system and can simultaneously track and classify up to 250 incoming missiles.

The five frigates are armed with a BlueIntercept SAM missiles system (model 1). They are fired sequentially at a minimum interval of 3 seconds per missile per ship. The BlueIntercept missiles fly at a speed of 1.1 kyds per second. Each BlueIntercept missile has a 0.70 probability of kill against a RedFire missile. The BlueIntercept missile has a maximum range of 72 kyds and a minimum range of 5 kyds (engagement inside 5 kyds is not possible due to safety stand-off).

Each frigate is armed only with 32 BlueIntercept missiles.

The RedFire missile flies at about Mach 1.25 (standard day, about 0.47 kyds per second) and is launched from a point at least 100 kyds from the AWS and frigates.

Each RedFire has a probability of hitting one of the ships at the force of 0.80, and given a hit, a probability of sinking a frigate = 0.30, and sinking an AWS = 0.15.

The RedFire uses a radar-seeker head and is more likely to hit a larger target (in proportion to the Radar Cross Section [RCS] of the ship). The AWS is considered to have two times the RSC of the frigate.

If a RedFire closes within 16 kyds of a targeted ship, then it will also be engaged by the frigate's main gun system (model 1). The main gun system has a 0.4 probability of killing an inbound RedFire. The main gun does not provide cross-platform defensive coverage. There is one main gun per frigate in the force. The total time for a full main gun engagement is 3 seconds (acquire, track, fire).

If RedFire closes within 10 kyds of frigate, then the decoy rounds of the frigate are activated. The decoy (model 1) has a 0.35 probability of attracting an inbound RedFire. The decoy does not provide cross-platform defensive coverage.

If a RedFire closes within 3 kyds of a targeted ship, then it can also be engaged by an ATTD system (model 1). A single ATTD system has a 0.3 probability of killing an inbound RedFire. ATTD do not provide cross-platform defensive coverage. There are two ATTD per ship in the force. The total time for a full ATTD engagement is 2 seconds (acquire, track, fire).

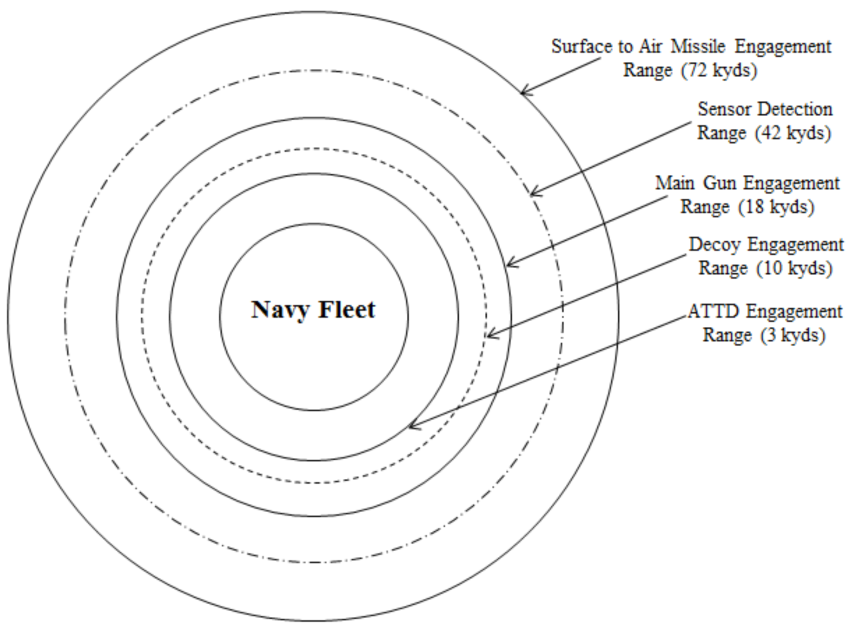
The capabilities of the defense systems are shown in Table 6**.**

Table 6. Fleet Defense Capabilities

Friendly Forces	Warship	RCS (relative to AWS)	BlueIntercept missile (per ship)	Main gun (per ship)	Decoy (per ship)	ATTD (per ship)
Amphibious Warfare Ships	4	10	-	-	-	2
Frigates	5	2.5	30	1	2	2

The defense detection and engagement range of the new multi-role stealth frigate includes SAM, main gun, decoy, and ATTD system, as shown in Figure 18.

Figure 18. Fleet Defense Detection and Engagement Range



Summary Table from the Scenario

RedFire Missile Specifications
Speed = 0.47 kyds/sec
Launched from a point at least 100 kyds from Amphibious Warfare ships(AWS)/Frigates
P(Hitting Ships) = 0.8
P(Sinking a Frigate|Hitting ships) = 0.3
P(Sinking an AWS|Hitting ships) = 0.15

Radar Sensor Detection against Missiles Specifications
Max Detection Range against missile = 42 kyd

TTD is log normally distributed with mean = 4sec and sd = 2sec
Maximum simultaneously tracking is 200 tracks

BlueIntercept Missile (SAM) Specifications
Fired sequentially at minimum interval of 3 sec per missile per ship
Speed = 1.1 kyds/sec
P(Kill against Redfire) is 0.7
Maximum Range = 72 kyds
Minimum engagement range of 5 kyds

Main Gun Defense Specifications
Engagement within 16kyds
P(Kill against leakers) = 0.4
Time to engage(Acquire, Track, Fire) is 3 sec

Decoy Specifications
Engagement within 10kyds
P(Kill against leakers) = 0.35

Area Terminal Type Defense (ATTD) Specifications
Engagement within 3kyds
P(Kill against leakers) = 0.3
Time to engage(Acquire, Track, Fire) is 2 sec

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APPENDIX B. FUNCTIONAL AND PHYSICAL ARCHITECTURE

Figure 19. Top-Level Functions of Maritime Escort Operation

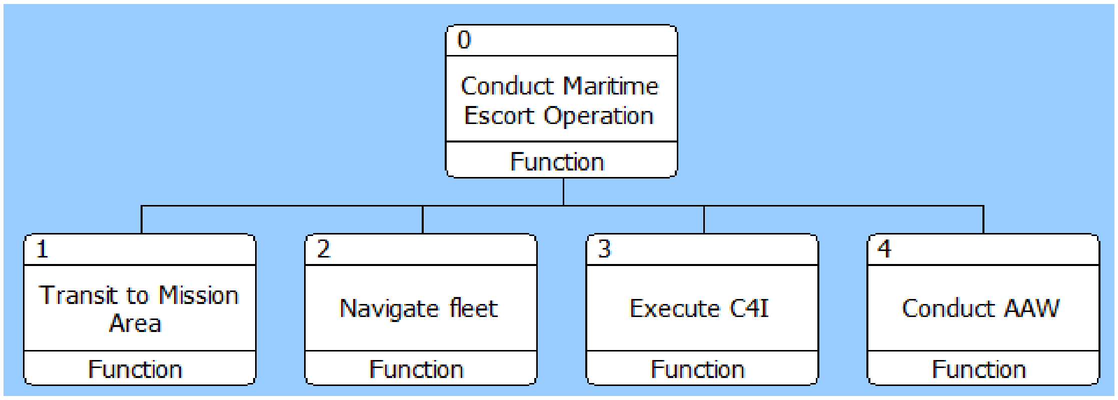

Figure 20. Second-Level Functions of Transit to Mission Area

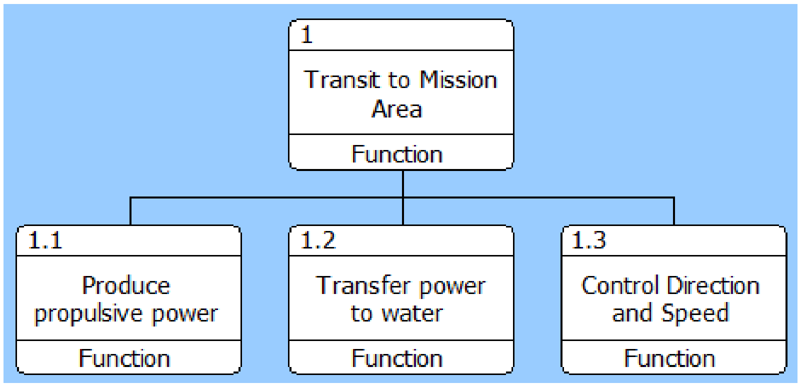

Figure 21. Second-Level Functions of Navigate fleet

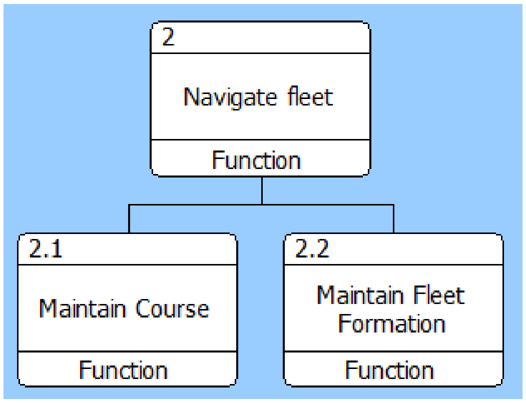

Figure 22. Second-Level Functions of Execute C4I

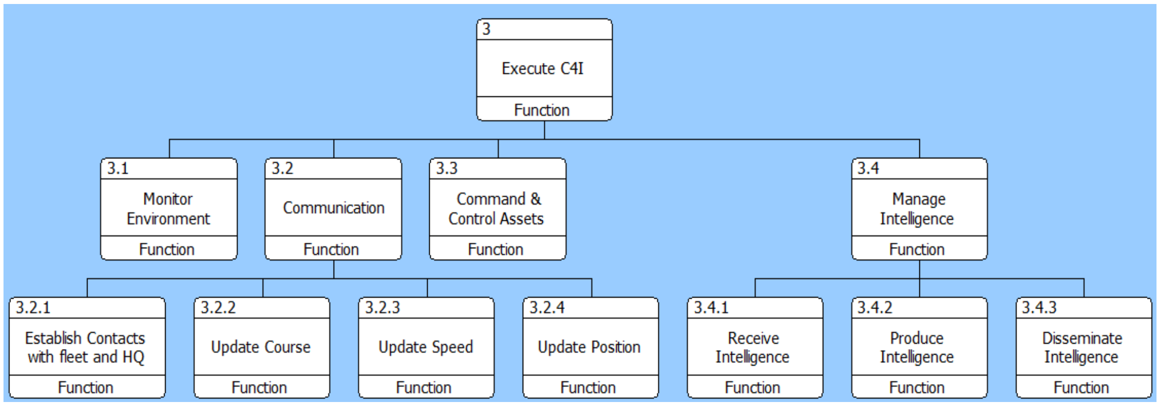

Figure 23. Second-Level Functions of Conduct AAW

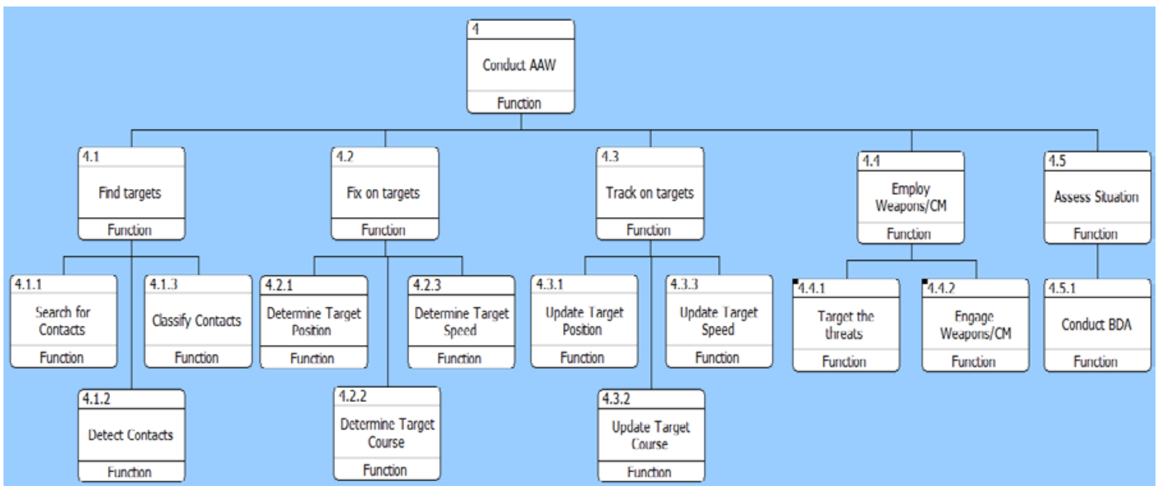

Table 7. Top-Level Functions Mapped to Physical System

Number	Function	Physical Component
0	Conduct Maritime Escort Operation	Frigate
1	Transit to Mission Area	Propulsion System
1.1	Produce Propulsive Power	Main Propulsion System
1.2	Transfer Power to Water	Ship Propellers
1.3	Control Direction and Speed	Engineering Operations Station
2	Navigate Fleet	Integrated Navigation System (INS)
2.1	Maintain Course	INS
2.2	Maintain Fleet Formation	CMS & INS
3	Execute C4I	C4I, CMS & ICS
3.1	Monitor Environment	ESM & Surveillance Radar
3.2	Communication	ICS
3.2.1	Establish Contacts with fleet and HQ	ICS
3.2.2	Update Course	GPS
3.2.3	Update Speed	Speed log
3.2.4	Update Position	GPS
3.3	Command & Control Assets	CMS
3.4	Manage Intelligence	C4I
3.4.1	Receive Intelligence	Antenna
3.4.2	Produce Intelligence	C4I
3.4.3	Disseminate Intelligence	HF Antenna/Satcom
4	Conduct AAW	CMS, Sensors, Weapons & Decoys
4.1	Find Targets	ESM, Surveillance Radar
4.1.1	Search for Contacts	ESM, Surveillance Radar
4.1.2	Detect Contacts	ESM, Surveillance Radar
4.1.3	Classify Contacts	Surveillance System with Identification Protocols
4.2	Fix on Targets	Surveillance Radar, FCR
4.2.1	Determine Target Position	ESM, Surveillance Radar
4.2.2	Determine Target Course	ESM, Surveillance Radar
4.2.3	Determine Target Speed	ESM, Surveillance Radar
4.3	Track on Targets	Surveillance Radar, FCR
4.3.1	Update Target Position	CMS & MLS
4.3.2	Update Target Course	CMS & MLS
4.3.3	Update Target Speed	CMS & MLS
4.4	Employ Weapons/CM	Weapons/Decoy
4.4.1	Target the Threats	FCR
4.4.1.1	Determine Firing Solution	CMS
4.4.1.2	Update Firing Solution	CMS
4.4.2	Engage Weapons/CM	SAM, Main Gun, ATTD, Decoy
4.4.2.1	Fire Weapons	SAM, Main Gun, ATTD
4.4.2.2	Fire Decoy	Decoy
4.5	Assess Situation	Surveillance Radar & FCR

Number	Function	Physical Component
4.5.1	Conduct BDA	CMS

APPENDIX C. PAYLOAD CONFIGURATION VS. MISSION CAPABILITIES

The baseline payload configuration is all the systems as shown in the payload configuration column of Table 8. This baseline configuration is used and built incrementally in the AOA.

Table 8. Payload Configuration vs. Mission Capabilities

		Multi Role Stealth Frigate Missions Capabilities						
	Payload Configuration	**SS**	**AAW**	**ASuW**	**ASW**	**CM**	**AC**	**MM**
Baseline	Integrated Navigation System (INS)	0	0	0	0	0	0	0
	Integrated Communication System (ICS)	0	0	0	0	0	0	0
	HELIVAS	0	0	0	0	0	0	0
	Combat Management System (CMS)	0	0	0	0	0	0	0
Main Sensors	Electronic Support Measures(ESM)	1	0	0	0	0	0	0
	Volume Search Surveillance Radar	2	0	0	0	0	0	0
	Fire Control Radar	3	0	0	0	0	0	0
SAM	Surface to Air Missile (SAM) - First Layer Defense	3	1	0	0	0	0	0
Main Gun	Main Gun - 76mm Gun - Second Layer Defense	3	2	1	0	0	0	0
ATTD	20mm Secondary Gun - Third Layer Defense	3	3	2	0	0	0	0
SSM	Surface to Surface Missile (SSM)	3	3	3	0	0	0	0
ASW	Anti Submarine Warfare (ASW) - Torpedo System	3	3	3	1	0	0	0
	Towed Array Sonar	3	3	3	2	0	0	0
	Torpedo Countermeasure	3	3	3	3	0	0	0
CM	Decoy System	3	3	3	3	1	0	0
Heli	Helicopter	3	3	3	3	1	1	0
Mission Module (MM)	Mission Module(UAV)	3	3	3	3	1	1	1
	Mission Module(USV)	3	3	3	3	1	1	2
	Mission Module(LDUUV)	3	3	3	3	1	1	3

SS	**Surveillance Systems**
AAW	**Anti Air Warfare**
ASuW	**Anti Surface Warfare**
ASW	**Anti Submarine Warfare**
CM	**Countermeasure**
MM	**Mission Module**
AC	**Aviation Capacity**

APPENDIX D. TOPSIDE DESIGN CONSIDERATIONS CHECKLIST

Table 9. Topside Design Considerations Checklist

S/N	Design Consideration	Items to Check	Checked	Remarks
1	Weapon Integration	i) Weapon Coverage (Arc of Firing)	√	
		ii) Interaction with Other Projectiles	√	
		iii) Gun Blast and Overpressure	√	
		iv) Limit Stops	√	
		v) Loading and Unloading of Ammo	√	Require a loading platform
		vi) Operation & Maintenance Space of Weapon	√	
		vii) Parking Position of weapon	√	
		viii) Foundation Frequency	√	
2	Blockage	i) Transmissions/Reception Arcs	√	
3	Access & Maintenance	i) Equipment Installation and Embarkation Route	√	
		ii) Equipment Maintenance & Repair Space	√	
		iii) Equipment Operation & Movement Space	√	
		iv) HF Antenna Whipping	√	Map movement zone
		v) Antenna Limit/Buffer Stop	√	
		vi) Ammunition Route		
4	Navigation	i) Meet SOLAS Requirement	√	
		ii) Seamanship Restriction	√	
		iii) Visibility	√	
5	Stability	i) Topside Weight	√	
		ii) Windage & Turbulence	√	
6	EMI/EMC Control Plan	i) Cable Penetration and Concealing	√	Zones indicated
		ii) Ventilation Opening and Shielded Doors	√	
7	Separation	i) From Other Equipment, Power/Frequency	√	
		ii) From Superstructures, Antennae Characteristics	√	
8	RADHAZ	i) Personnel (HERP)	√	
		ii) Explosives Fuel (HERF) /Replenishment at Sea(RAS)	√	
		iii) Aviation (HIRF)	√	
		iv) Ordnance (HERO)	√	

S/N	Design Consideration	Items to Check	Checked	Remarks
9	Ballistic Protection	i) Armor Plate Protection Coverage	√	
10	Superstructure Material	i) Steel, Aluminum, Composite (Fiber Reinforced)	√	Material : composite
		ii) Galvanic Corrosion Issue	√	
11	RAS	i) Routes	√	
		ii) Positions	√	
		iii) Special Handling	√	
12	Missile Integration & Efflux	i) Personnel Safety	√	
		ii) Missile Installation and Embarkation Route	√	
		iii) Efflux Temperature Profile (Missile Area)	√	
		iv) Efflux Pressure Profile (Missile Area)	√	
		v) Toxic Gases Component of Efflux	√	
		vi) Blast Panel	√	
		vii) Interaction with Other Projectiles	√	e.g., SAM and decoys
		viii) Firing Arc and Clearance Zone (Conical Shape)	√	
		ix) Ejection of Debris	√	
		x) Missile Electromagnetic Susceptibility	√	
		xi) Foundation Strength Requirements, Alignment, & Foundation Frequency	√	
		xii) Ammo Safety and Fire Fighting Capability	√	
13	Alignment of Topside Equipment with Ship's Master Datum Plate	i) Static and Dynamic	√	
		ii) Flexure	√	
14	Shock & Vibration	i) Equipment Able to Qualify to Withstand the Shock & Vibration	√	
15	Funnel Gases	i) Temperature of Exhaust Gases	√	250 degree Celsius at 1m away
		ii) Direction of Exhaust Gases	√	
16	Green Seas	i) Equipment Able to Qualify to Withstand the Sea Spray & IP Rating	√	
17	Radar Cross Section		√	
18	IR Signature		X	
19	Laser Safety	i) Check the Laser Finder Is Eye Safe	√	
20	Magazine Location	i) Check the Ventilation of Ammo Locker & Handling	√	

S/N	Design Consideration	Items to Check	Checked	Remarks
21	Damage Control/NBC	i) Check that Ventilation Openings, Doors, and Louvers Meet NBC Requirements	√	Require supplier to validate
22	Docking/Berthing Considerations		√	
23	Electromagnetic Interference	i) Frequency Spectrum Utilization Chart	√	
		ii) Source & Victim Matrix	√	
		ii) Multipath Effects	√	Shaping required
24	Aviation Interactions	i) Helicopter Operation	√	
		ii) Air Turbulence	√	
		iii) Recovery of UAV	√	
		Iv Flight Deck Requirement	√	
25	Shielding/Ground Planes	i) EMI/EMC Shielding and Isolation Purposes	√	
26	Compartment	i) Requirement of Blast-Off Panel	√	
	Overpressure			
27	Replenishment at Sea (RAS)	i) RAS Operation and Requirement	√	
		ii) Hazardous Zone Consideration	√	
28	Boat Handling	i) Boats Operation & Boat Handling Equipment	√	
29	Life Saving Equipment	i) Meet SOLAS Requirement	√	
		ii) Size of the Passageways	√	
30	Escape Route & Walkway	i) Class Requirement on Escape Route (w:900mm)	√	
		ii) Handrails, Ladder, Guard Ropes for Safe Access	√	
31	Structural Integrity	i) Natural Frequency of Mast and Foundation	√	
		ii) Stiffness, Flatness, & Strength	√	
32	Thermal Expansion of Foundation	i) Thermal Analysis	√	
33	Hazardous Zone	i) Class Requirement	√	
34	Mast Height	i) Radar Required Performance	√	

S/N	Design Consideration	Items to Check	Checked	Remarks
	Restriction			
35	Scenario Modeling	i) Range to Target Model	√	
36	Lightning Protection		√	
37	Human Ergonomics	i) Based on Required Standards	√	
38	Future Growth (FFBNW/FTR)	i) Mission Modules Requirement	√	

APPENDIX E. SHIP RESEARCH DATABASE

The length, beam, draft, displacement, and speed information are referenced from *IHS Jane's Fighting Ships* (Saunders 2014). The beam draft ratio and length displacement ratio are calculated.

No	Class	Country	Length (m)	Beam (m)	Draft (m)	Beam Draft Ratio Kb = B/T	Length Displacement Ratio (M)	Displacement (tons)	Speed (knots)
1	Formidable	Singapore	114.8	16..3	6.0	2.71	7.538	3200	27
2	Fremm	France	142.0	20.0	5.0	4.00	7.114	6000	27
3	Anzac	Australia	118.0	14.8	4.4	3.40	7.481	3600	27
4	Valour	South Africa	121.0	16.3	6.0	2.75	7.581	3700	28
5	La Fayette	France	125.0	15.4	4.8	3.21	7.064	3200	25
6	Fridtjof Nansen	Norway	134.0	16.8	4.6	3.65	7.081	5290	26
7	Sachsen	Germany	143.0	17.4	6.0	2.91	7.380	5800	29
8	Alvaro de Bazan	Spain	146.7	18.6	4.8	3.92	7.260	6391	28.5
9	Type 054	China	134.1	16.0	5.0	3.20	7.224	4053	27
				Average		3.34	7.32		

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APPENDIX F. TOPSIDE SIZING MODEL PARAMETERS AND DESIGNS

Table 10. Design Parameters of the Topside Sizing Model (Part 1)

Design Parameters	Length Proportion
Front space of forecastle of ship	0.065
Forward block (inclusive of fwd stacked mast)	0.14
Aft block (inclusive of aft stacked mast and funnel)	0.11
Hangar	3m added to overall hangar length

Figure 24 shows the ship design with 2 ATTD, and Figure 25 shows the ship design with 3 ATTD.

Figure 24. Ship Design with Two ATTD

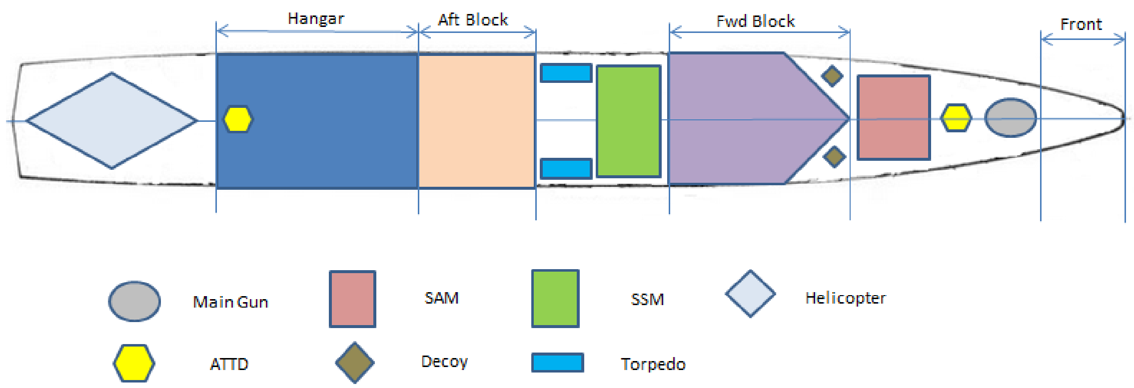

Figure 25. Ship Design with Three ATTD

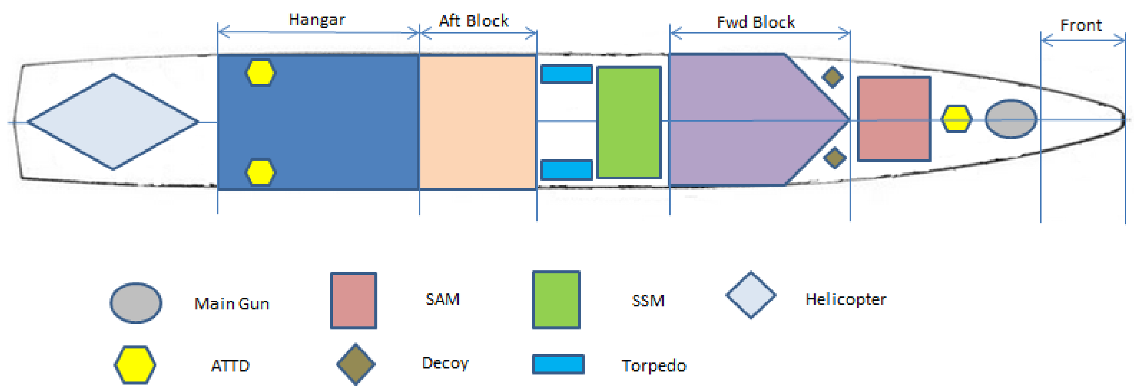

Table 11. Design Parameters of the Topside Sizing Model (Part 2)

No	Payload Configuration	Location	Length of Model 1 (m)	Model 1 Additional Required Space including design tolerances (m)	Length of Model 2 (m)	Model 2 Additional Required Space including design tolerances (m)	Length of Model 3 (m)	Model 3 Additional Required Space including design tolerances (m)
1	Integrated Navigation Systems (INS)	on stacked mast and bridge top of superstructure and inboard						
2	Integrated Communication System (ICS)	on topside and inboard						
3	Surveillance System	on stacked mast(fwd block)						
4	Electronic Support Measures(ESM)	on stacked mast(aft block)						
5	Fire Control Systems	on bridge top (fwd block)						
6	Combat Management System	inboard						
7	Decoy System	on topside	0	0.65	0	0.8775		
8	Main Gun	on topside	0	0.8	0	1.08		
9	Area Terminal Type Defense (ATTD) system	one in front of SAM(C), second(C/port) and third(stbd) on topside(on hangar roof)	0	0.65	4	0.6955	4	0.78
10	Heavy Machine Guns	on topside(bridge wings)						
11	Surface to Surface Missile (SSM)	on topside	3.60	2				
12	Surface to Air Missile (SAM)	on topside	4.80	2.5	6.40	3.375		
13	Ammunition	inboard except RUL						
14	Helicopter	on topside	0	0				
15	Heli Visual Aids System (HELIVAS)	on topside(on hangar roof)	0	0				
16	Anti Submarine Warfare (ASW) -	on topside	0	0.65				
17	Towed Array Sonar	below deck						
18	Torpedo Countermeasure	on topside(on hangar roof)	0	0.65				
19	Mission Module(UAV)	on topside (modular concept) - stored in hangar, deployed on helideck						
20	Mission Module(USV)	on topside (modular concept) - kept in boat area						
21	Mission Module(LDUUV)	on topside (modular concept) - kept in 1st deck deployed from 1st deck						

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APPENDIX G. DESIGN OF EXPERIMENT: MINITAB ANALYSIS AND RESULTS

Table 12. Minitab Inputs and Outputs for Scenario 1

Detection Range	Launch Interval	BI Max Range	BI Max Speed	BI P(Kill)	Main Gun	Main Gun	Decoy	ATTD Range	ATTD P(Kill)	RCS	Frigate sunk
42	1	72	1.1	0.7	16	0.4	0.5	3	0.4	0.9	0.38
80	1	100	1.1	0.95	16	0.4	0.5	6	0.3	0.9	0.098
80	1	100	1.1	0.95	24	0.4	0.5	3	0.4	0.6	0
80	3	72	1.5	0.7	24	0.6	0.35	6	0.3	0.6	0.008
80	1	72	1.1	0.95	16	0.6	0.35	6	0.3	0.9	0.196
42	1	100	1.1	0.7	16	0.6	0.35	3	0.4	0.9	0.796
80	1	72	1.5	0.7	24	0.6	0.5	3	0.4	0.6	0.008
42	1	72	1.5	0.95	24	0.4	0.35	6	0.3	0.6	0
80	1	72	1.1	0.7	24	0.4	0.35	3	0.3	0.9	0.81
80	1	72	1.1	0.7	16	0.4	0.35	6	0.4	0.6	0.028
80	1	100	1.1	0.7	24	0.6	0.5	3	0.3	0.9	0.54
80	3	72	1.5	0.7	16	0.6	0.35	3	0.4	0.9	0.842
80	3	100	1.5	0.95	16	0.6	0.5	3	0.3	0.6	0
42	1	100	1.1	0.95	24	0.4	0.35	6	0.4	0.9	0.106
42	3	72	1.1	0.95	16	0.6	0.35	6	0.4	0.6	0.004
80	3	100	1.5	0.95	24	0.6	0.5	6	0.4	0.9	0.004
42	3	72	1.5	0.7	24	0.6	0.5	3	0.3	0.9	0.772
80	1	100	1.5	0.7	16	0.4	0.35	6	0.3	0.9	0.356
42	1	100	1.5	0.95	16	0.6	0.5	3	0.4	0.9	0.242
42	3	100	1.1	0.95	24	0.4	0.5	3	0.3	0.9	0.744
80	3	100	1.1	0.95	16	0.4	0.35	3	0.4	0.9	0.574
80	3	72	1.5	0.95	16	0.4	0.35	3	0.3	0.6	0.006
80	3	72	1.5	0.95	24	0.4	0.35	6	0.4	0.9	0.102
80	1	100	1.5	0.95	24	0.6	0.35	3	0.3	0.9	0.462
42	1	100	1.1	0.95	16	0.4	0.35	3	0.3	0.6	0.002
42	3	100	1.5	0.95	24	0.6	0.35	3	0.4	0.6	0.01
42	1	72	1.1	0.95	16	0.6	0.5	3	0.3	0.6	0
42	3	100	1.5	0.95	16	0.6	0.35	6	0.3	0.9	0.676
42	3	72	1.1	0.7	24	0.4	0.35	3	0.4	0.6	0.326
42	3	72	1.1	0.95	24	0.6	0.35	3	0.3	0.9	0.708
42	3	100	1.5	0.7	24	0.4	0.35	3	0.3	0.9	0.952
42	3	100	1.5	0.7	16	0.4	0.35	6	0.4	0.6	0.18
80	3	100	1.1	0.95	24	0.4	0.35	6	0.3	0.6	0
42	1	72	1.5	0.7	24	0.6	0.35	6	0.4	0.9	0.378
42	1	72	1.5	0.95	16	0.4	0.35	3	0.4	0.9	0.572
80	3	100	1.1	0.7	24	0.6	0.35	6	0.4	0.9	0.35
42	3	100	1.1	0.95	16	0.4	0.5	6	0.4	0.6	0.004
80	1	100	1.1	0.7	16	0.6	0.5	6	0.4	0.6	0.002
80	1	72	1.5	0.7	16	0.6	0.5	6	0.3	0.9	0.466
42	3	100	1.1	0.7	24	0.6	0.5	3	0.4	0.6	0.082
42	1	72	1.5	0.7	16	0.6	0.35	3	0.3	0.6	0.094
80	3	100	1.5	0.7	16	0.4	0.5	3	0.4	0.9	0.754
42	1	100	1.5	0.95	24	0.6	0.5	6	0.3	0.6	0
80	1	72	1.1	0.95	24	0.6	0.35	3	0.4	0.6	0
80	3	100	1.5	0.7	24	0.4	0.5	6	0.3	0.6	0.01
80	3	72	1.1	0.7	24	0.4	0.5	6	0.4	0.9	0.342
80	3	72	1.1	0.7	16	0.4	0.5	3	0.3	0.6	0.112
42	1	100	1.1	0.7	24	0.6	0.35	6	0.3	0.6	0.018
80	1	72	1.5	0.95	16	0.4	0.5	6	0.4	0.6	0
80	1	72	1.5	0.95	24	0.4	0.5	3	0.3	0.9	0.292
42	3	72	1.5	0.7	16	0.6	0.5	6	0.4	0.6	0.052
80	3	72	1.1	0.95	24	0.6	0.5	6	0.3	0.6	0
42	3	72	1.5	0.95	24	0.4	0.5	3	0.4	0.6	0.032
42	1	72	1.1	0.7	24	0.4	0.5	6	0.3	0.6	0.018
42	3	100	1.1	0.7	16	0.6	0.5	6	0.3	0.9	0.74
42	3	72	1.1	0.7	16	0.4	0.35	6	0.3	0.9	0.952
42	3	72	1.5	0.95	16	0.4	0.5	6	0.3	0.9	0.588
80	1	100	1.5	0.95	16	0.6	0.35	6	0.4	0.6	0
42	1	100	1.5	0.7	24	0.4	0.5	6	0.4	0.9	0.324
80	1	100	1.5	0.7	24	0.4	0.35	3	0.4	0.6	0.076
80	3	100	1.1	0.7	16	0.6	0.35	3	0.3	0.6	0.104
80	3	72	1.1	0.95	16	0.6	0.5	3	0.4	0.9	0.322
42	1	72	1.1	0.95	24	0.6	0.5	6	0.4	0.9	0.004
42	1	100	1.5	0.7	16	0.4	0.5	3	0.3	0.6	0.132

Table 13. Minitab Inputs and Outputs for Scenario 2

Detection Range	Launch Interval	BI Max Range	BI Max Speed	BI P(Kill)	Main Gun Range	Main Gun P(Kill)	Decoy P(Kill)	ATTD Range	ATTD P(Kill)	RCS	AWS	Frigate
80	3	72	1.5	0.95	16	0.4	0.35	3	0.3	2.5	2.24	0.012
80	1	72	1.1	0.95	16	0.6	0.35	6	0.3	5	1.16	0.006
80	3	72	1.1	0.7	16	0.4	0.5	3	0.3	2.5	3.37	0.048
42	1	72	1.5	0.7	24	0.6	0.35	6	0.4	5	2.32	0
42	3	72	1.5	0.7	24	0.6	0.5	3	0.3	5	3.36	0.05
80	3	100	1.1	0.95	24	0.4	0.35	6	0.3	2.5	1.64	0
42	1	100	1.5	0.95	16	0.6	0.5	3	0.4	5	1.56	0.004
42	3	72	1.1	0.7	16	0.4	0.35	6	0.3	5	3.08	0.298
80	3	100	1.1	0.7	16	0.6	0.35	3	0.3	2.5	3.3	0.018
80	3	100	1.5	0.7	24	0.4	0.5	6	0.3	2.5	3.01	0.004
42	3	100	1.1	0.7	24	0.6	0.5	3	0.4	2.5	3.57	0.004
42	3	72	1.5	0.7	16	0.6	0.5	6	0.4	2.5	3.42	0.004
42	3	100	1.5	0.7	16	0.4	0.35	6	0.4	2.5	3.41	0.014
80	3	100	1.1	0.95	16	0.4	0.35	3	0.4	5	2.1	0.008
80	1	100	1.1	0.95	24	0.4	0.5	3	0.4	2.5	2.09	0.006
80	1	72	1.1	0.7	16	0.4	0.35	6	0.4	2.5	2.87	0.008
42	1	100	1.1	0.7	24	0.6	0.35	6	0.3	2.5	3.06	0
42	1	100	1.5	0.7	24	0.4	0.5	6	0.4	5	2.23	0.008
80	1	72	1.5	0.95	24	0.4	0.5	3	0.3	5	1.76	0.016
80	1	72	1.5	0.7	24	0.6	0.5	3	0.4	2.5	2.96	0.012
42	3	72	1.1	0.95	24	0.6	0.35	3	0.3	5	2.89	0.016
42	1	72	1.1	0.95	24	0.6	0.5	6	0.4	5	0.72	0
42	1	100	1.5	0.7	16	0.4	0.5	3	0.3	2.5	3.34	0.056
80	3	100	1.5	0.95	24	0.6	0.5	6	0.4	5	0.74	0
42	3	72	1.5	0.95	16	0.4	0.5	6	0.3	5	2.43	0.04
42	3	72	1.1	0.7	24	0.4	0.35	3	0.4	2.5	3.6	0.05
80	1	100	1.5	0.95	24	0.6	0.35	3	0.3	5	1.77	0.002
42	1	72	1.5	0.95	16	0.4	0.35	3	0.4	5	1.65	0.036
42	1	100	1.1	0.95	24	0.4	0.35	6	0.4	5	0.67	0.002
42	3	100	1.1	0.95	16	0.4	0.5	6	0.4	2.5	2.73	0.002
42	3	72	1.1	0.95	16	0.6	0.35	6	0.4	2.5	2.77	0
80	1	100	1.1	0.95	16	0.4	0.5	6	0.3	5	1.16	0.004
80	3	72	1.5	0.7	16	0.6	0.35	3	0.4	5	2.81	0.088
42	1	72	1.1	0.7	24	0.4	0.5	6	0.3	2.5	3.06	0
42	1	72	1.5	0.7	16	0.6	0.35	3	0.3	2.5	3.3	0.024
80	1	100	1.5	0.7	16	0.4	0.35	6	0.3	5	2.56	0.116
80	3	72	1.5	0.7	24	0.6	0.35	6	0.3	2.5	3.05	0.002
80	1	72	1.1	0.95	24	0.6	0.35	3	0.4	2.5	2.08	0
42	3	100	1.1	0.95	24	0.4	0.5	3	0.3	5	2.9	0.074
42	1	72	1.1	0.95	16	0.6	0.5	3	0.3	2.5	2.23	0
80	3	100	1.1	0.7	24	0.6	0.35	6	0.4	5	2.29	0
80	3	72	1.1	0.95	24	0.6	0.5	6	0.3	2.5	1.63	0
80	3	72	1.1	0.95	16	0.6	0.5	3	0.4	5	1.67	0.004
42	1	100	1.1	0.7	16	0.6	0.35	3	0.4	5	2.94	0.114
80	1	100	1.1	0.7	16	0.6	0.5	6	0.4	2.5	2.87	0
42	3	100	1.5	0.7	24	0.4	0.35	3	0.3	5	3.35	0.514
80	1	100	1.5	0.7	24	0.4	0.35	3	0.4	2.5	3.2	0.02
42	3	100	1.1	0.7	16	0.6	0.5	6	0.3	5	3.16	0.044
42	3	100	1.5	0.95	16	0.6	0.35	6	0.3	5	2.41	0.038
80	1	72	1.1	0.7	24	0.4	0.35	3	0.3	5	3.01	0.198
80	3	72	1.5	0.95	24	0.4	0.35	6	0.4	5	0.75	0.002
42	1	72	1.1	0.7	16	0.4	0.5	3	0.4	5	2.85	0.158
42	1	100	1.1	0.95	16	0.4	0.35	3	0.3	2.5	1.63	0.028
80	3	100	1.5	0.7	16	0.4	0.5	3	0.4	5	1.65	0.044
80	3	100	1.5	0.95	16	0.6	0.5	3	0.3	2.5	2.25	0
80	3	72	1.1	0.7	24	0.4	0.5	6	0.4	5	2.3	0.006
80	1	100	1.1	0.7	24	0.6	0.5	3	0.3	5	2.97	0.014
42	1	72	1.5	0.95	24	0.4	0.35	6	0.3	2.5	1.67	0
42	3	100	1.5	0.95	24	0.6	0.35	3	0.4	2.5	3.14	0.004
42	3	72	1.5	0.95	24	0.4	0.5	3	0.4	2.5	3.15	0.004
80	1	100	1.5	0.95	16	0.6	0.35	6	0.4	2.5	1.21	0
80	1	72	1.5	0.95	16	0.4	0.5	6	0.4	2.5	1.21	0
42	1	100	1.5	0.95	24	0.6	0.5	6	0.3	2.5	1.61	0
80	1	72	1.5	0.7	16	0.6	0.5	6	0.3	5	2.54	0.014

APPENDIX H. SENSITIVITY ANALYSIS PARAMETERS AND RESULTS

Table 14. Sensitivity Analysis Parameters

	Payload Configuration	Unit Cost($M)	System Performance Specifications: Launch Interval (s)	Sensor Detection Range against missile (kyds)	SAM Range (kyds)	SAM speed (kyds/s)	SAM Pk	Main Gun Range (kyds)	Main Gun Pk	Decoy Pk	ATTD Pk	ATTD Range (kyds)
Baseline	Integrated Navigation System (INS)	1.2	-	-	-	-	-	-	-	-	-	
	Integrated Communication System (ICS)	1.5	-	-	-	-	-	-	-	-	-	
	HELIVAS	1	-	-	-	-	-	-	-	-	-	
	Combat Management System (CMS) - Model 1	10	3	-	-	-	-	-	-	-	-	
	Combat Management System (CMS) - Model 2	20	1	-	-	-	-	-	-	-	-	
Main Sensors	Electronic Support Measures(ESM)	3	-	-	-	-	-	-	-	-	-	
	Volume Search Surveillance Radar Model 1	10	-	42	-	-	-	-	-	-	-	
	Volume Search Surveillance Radar Model 2	20	-	80	-	-	-	-	-	-	-	
	Fire Control Radar	8	-	-	-	-	-	-	-	-	-	
SAM	Surface to Air Missile (SAM) Model 1 - First Layer Defense	18	-	-	72	1.1	0.7	-	-	-	-	
	Surface to Air Missile (SAM) Model 2 - First Layer Defense	30	-	-	100	1.5	0.95	-	-	-	-	
Main Gun	Main Gun - 127mm Gun - Second Layer Defense	19	-	-	-	-	-	24	0.6	-	-	
	Main Gun - 76mm Gun - Second Layer Defense	11	-	-	-	-	-	16	0.4	-	-	
ATTD	Close in Weapon System (CIWS) - Third Layer Defense Model 3	15	-	-	-	-	-	-	-	-	0.95 (0.80)	12 (10)
	30mm Secondary Gun - Third Layer Defense Model 2	5	-	-	-	-	-	-	-	-	0.4	6
	20mm Secondary Gun - Third Layer Defense Model 1	2	-	-	-	-	-	-	-	-	0.3	3
SSM	Surface to Surface Missile (SSM)	15	-	-	-	-	-	-	-	-	-	
ASW	Anti Submarine Warfare (ASW) - Torpedo System	8	-	-	-	-	-	-	-	-	-	
	Towed Array Sonar	5	-	-	-	-	-	-	-	-	-	
	Torpedo Countermeasure	3	-	-	-	-	-	-	-	-	-	
CM	Decoy System Model 1	6	-	-	-	-	-	-	-	0.35	-	
	Decoy System Model 2	10	-	-	-	-	-	-	-	0.5	-	
Heli	Helicopter	50	-	-	-	-	-	-	-	-	-	
Mission Module (MM)	Mission Module(UAV)	4	-	-	-	-	-	-	-	-	-	
	Mission Module(USV)	2.5	-	-	-	-	-	-	-	-	-	
	Mission Module(LDUUV)	2	-	-	-	-	-	-	-	-	-	

	Assumptions	
1	Cost of RCS improvement	$ 15 M per frigate
2	Cost per meter length of frigate is	$ 3.25 M
3	RCS has no change to length and beam and displacement	
4	Topside Sizing Model is based on the following design parameters: front block length = 0.14, aft block length = 0.11, hangar length = 3m added and front = 0.065	

Table 15. Sensitivity Analysis Results

Option 1 (1)			Option 2 (2)			Option 3 (3)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade missile type			RCS improvement to ship & payload design			Upgrade Main Gun		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
BI P(Kill)	0.95		RCS	2.5		Main Gun P(Kill)	0.6	
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	2.902	0.404	Mean	3.664	0.28	Mean	3.406	0.47
Standard Error	0.039139	0.02747869	Standard Error	0.024319	0.02272075	Standard Error	0.03281	0.027924174
Median	3	0	Median	4	0	Median	4	0
Mode	3	0	Mode	4	0	Mode	4	0
Standard Deviation	0.875173	0.61444209	Standard Deviation	0.543779	0.508051407	Standard Deviation	0.733649	0.624403523
Sample Variance	0.765928	0.37753908	Sample Variance	0.295695	0.258116232	Sample Variance	0.53824	0.38987976
Kurtosis	0.163053	1.23604761	Kurtosis	1.529852	2.589747411	Kurtosis	0.646361	0.56975674
Skewness	-0.61883	1.35914004	Skewness	-1.43029	1.700522216	Skewness	-1.07815	1.080841891
Range	4	3	Range	3	3	Range	3	3
Minimum	0	0	Minimum	1	0	Minimum	1	0
Maximum	4	3	Maximum	4	3	Maximum	4	3
Sum	1451	202	Sum	1832	140	Sum	1703	235
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.064498	0.04528248	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.040075	0.037441818	Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.054068	0.04601661
Confidence(90%) of more than 99% chance of survivability	0.935502	0.95471752	Confidence(90%) of more than 99% chance of survivability	0.959925	0.962558182	Confidence(90%) of more than 99% chance of survivability	0.945932	0.95398339
Results	**Fail**	**Fail**	Results	**Fail**	**Fail**	Results	**Fail**	**Fail**

Option 4(4)			Option 5 (5)			Option 6 (6)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade ATTD			Upgrade ATTD			Upgrade Decoy		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
ATTD P(Kill)	0.4		ATTD Range	6	kyds	Decoy P(Kill)	0.5	
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	3.346	0.84	Mean	3.14	0.284	Mean	3.372	0.686
Standard Error	0.031473	0.03643425	Standard Error	0.036489	0.02134477	Standard Error	0.032945	0.034075361
Median	3	1	Median	3	0	Median	4	1
Mode	4	1	Mode	3	0	Mode	4	0
Standard Deviation	0.703757	0.8146947	Standard Deviation	0.815924	0.477283563	Standard Deviation	0.736683	0.761948246
Sample Variance	0.495275	0.66372745	Sample Variance	0.665731	0.227799599	Sample Variance	0.542701	0.58056513
Kurtosis	0.025591	0.06483501	Kurtosis	0.345908	0.443292356	Kurtosis	1.367723	0.129842123
Skewness	-0.77494	0.72567724	Skewness	-0.79601	1.289831244	Skewness	-1.10699	0.870477697
Range	3	4	Range	4	2	Range	4	3
Minimum	1	0	Minimum	0	0	Minimum	0	0
Maximum	4	4	Maximum	4	2	Maximum	4	3
Sum	1673	420	Sum	1570	142	Sum	1686	343
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.051865	0.06004048	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.060131	0.035174323	Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.054291	0.056153231
Confidence(90%) of more than 99% chance of survivability	0.948135	0.93995952	Confidence(90%) of more than 99% chance of survivability	0.939869	0.964825677	Confidence(90%) of more than 99% chance of survivability	0.945709	0.943846769
Results	**Fail**	**Fail**	Results	**Fail**	**Fail**	Results	**Fail**	**Fail**

Option 7 (7)			Option 8 (8)			Option 9 (1,2)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade Sensor			Upgrade CMS			Upgrade missile type		
						RCS improvement to ship & payload design		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
Detection Range	80	kyds	Launch Interval	1	sec	BI P(Kill)	0.95	
						RCS	2.5	
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	2.978	0.494	Mean	2.98	0.46	Mean	3.21	0.066
Standard Error	0.037388	0.03042663	Standard Error	0.039526	0.030110019	Standard Error	0.035075	0.011114633
Median	3	0	Median	3	0	Median	3	0
Mode	3	0	Mode	3	0	Mode	4	0
Standard Deviation	0.836011	0.68036004	Standard Deviation	0.883834	0.673280486	Standard Deviation	0.784302	0.248530753
Sample Variance	0.698914	0.46288978	Sample Variance	0.781162	0.453306613	Sample Variance	0.61513	0.061767535
Kurtosis	-0.37799	1.19388628	Kurtosis	-0.03021	1.294335613	Kurtosis	-0.637	10.33723836
Skewness	-0.47513	1.2676006	Skewness	-0.66039	1.352628682	Skewness	-0.56306	3.506551741
Range	3	3	Range	4	3	Range	3	1
Minimum	1	0	Minimum	0	0	Minimum	1	0
Maximum	4	3	Maximum	4	3	Maximum	4	1
Sum	1489	247	Sum	1490	230	Sum	1605	33
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.061611	0.05014043	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.065136	0.049618691	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.057801	0.018315948
Confidence(90%) of more than 99% chance of survivability	0.938389	0.94985957	Confidence(90%) of more than 99% chance of survivability	0.934864	0.950381309	Confidence(90%) of more than 99% chance of survivability	0.942199	0.981684052
Results	**Fail**	**Fail**	Results	**Fail**	**Fail**	Results	**Fail**	**Fail**

Option 10 (1,3)			Option 11 (1,4)			Option 12 (1,2,3)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade missile type			Upgrade missile type			Upgrade missile type		
Upgrade Main Gun			Upgrade ATTD			RCS improvement to ship & payload design		
						Upgrade Main Gun		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
BI P(Kill)	0.95		BI P(Kill)	0.95		BI P(Kill)	0.95	
Main Gun P(Kill)	0.6		ATTD P(Kill)	0.4		RCS	2.5	
						Main Gun P(Kill)	0.6	
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	2.9	0.158	Mean	2.776	0.282	Mean	3.254	0.02
Standard Error	0.039486	0.01818608	Standard Error	0.040976	0.022404373	Standard Error	0.033184	0.006267261
Median	3	0	Median	3	0	Median	3	0
Mode	3	0	Mode	3	0	Mode	3	0
Standard Deviation	0.882926	0.40665309	Standard Deviation	0.916244	0.500977001	Standard Deviation	0.742014	0.14014021
Sample Variance	0.779559	0.16536673	Sample Variance	0.839503	0.250977956	Sample Variance	0.550585	0.019639279
Kurtosis	-0.28172	6.1811685	Kurtosis	-0.22336	1.424735057	Kurtosis	-0.22652	45.48597214
Skewness	-0.4876	2.57059353	Skewness	-0.4365	1.53360804	Skewness	-0.65279	6.877793456
Range	4	2	Range	4	2	Range	3	1
Minimum	0	0	Minimum	0	0	Minimum	1	0
Maximum	4	2	Maximum	4	2	Maximum	4	1
Sum	1450	79	Sum	1388	141	Sum	1627	10
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.065069	0.02996908	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.067524	0.036920457	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.054684	0.0103279
Confidence(90%) of more than 99% chance of survivability	0.934931	0.97003092	Confidence(90%) of more than 99% chance of survivability	0.932476	0.963079543	Confidence(90%) of more than 99% chance of survivability	0.945316	0.9896721
Results	**Fail**	**Fail**	Results	**Fail**	**Fail**	Results	**Fail**	**Fail**

Option 13 (1,2,4)			Option 14 (1,2,7)			Option 15 (1,2,3,4)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade missile type			Upgrade missile type			Upgrade missile type		
RCS improvement to ship & payload design			RCS improvement to ship & payload design			RCS improvement to ship & payload design		
Upgrade ATTD			Upgrade Sensor			Upgrade Main Gun		
						Upgrade ATTD		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
BI P(Kill)	0.95		BI P(Kill)	0.95		BI P(Kill)	0.95	
RCS	2.5		RCS	2.5		RCS	2.5	
ATTD P(Kill)	0.4		Detection Range	80	kyds	Main Gun P(Kill)	0.6	
						ATTD P(Kill)	0.4	
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	3.21	0.064	Mean	2.206	0.006	Mean	3.208	0.004
Standard Error	0.034383	0.01095665	Standard Error	0.041697	0.003457153	Standard Error	0.035042	0.002825592
Median	3	0	Median	2	0	Median	3	0
Mode	3	0	Mode	2	0	Mode	3	0
Standard Deviation	0.768819	0.24499806	Standard Deviation	0.932364	0.077304281	Standard Deviation	0.783559	0.063182149
Sample Variance	0.591082	0.06002405	Sample Variance	0.869303	0.005975952	Sample Variance	0.613964	0.003991984
Kurtosis	0.344787	10.8131816	Kurtosis	-0.24719	163.3132451	Kurtosis	-0.27011	247.4839115
Skewness	-0.72369	3.57350592	Skewness	-0.12275	12.83199139	Skewness	-0.65945	15.76369195
Range	4	1	Range	4	1	Range	3	1
Minimum	0	0	Minimum	0	0	Minimum	1	0
Maximum	4	1	Maximum	4	1	Maximum	4	1
Sum	1605	32	Sum	1103	3	Sum	1604	2
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.05666	0.0180556	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.068712	0.005697087	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.057746	0.004656329
Confidence(90%) of more than 99% chance of survivability	0.94334	0.9819444	Confidence(90%) of more than 99% chance of survivability	0.931288	0.994302913	Confidence(90%) of more than 99% chance of survivability	0.942254	0.995343671
Results	**Fail**	**Fail**	Results	**Fail**	**Pass**	Results	**Fail**	**Pass**

Option 16 (1,2,3,5)			Option 17 (1,2,3,4,5)			Option 18 (1,2,3,4,5,7)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade missile type			Upgrade missile type			Upgrade missile type		
RCS improvement to ship & payload design			RCS improvement to ship & payload design			RCS improvement to ship & payload design		
Upgrade Main Gun			Upgrade Main Gun			Upgrade Main Gun		
Upgrade ATTD			Upgrade ATTD			Upgrade ATTD		
						Upgrade Sensor		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
BI P(Kill)	0.95		BI P(Kill)	0.95		BI P(Kill)	0.95	
RCS	2.5		RCS	2.5		RCS	2.5	
Main Gun P(Kill)	0.6		Main Gun P(Kill)	0.6		Main Gun P(Kill)	0.6	
ATTD Range	6	kyds	ATTD P(Kill)	0.4		ATTD P(Kill)	0.4	
			ATTD Range	6	kyds	ATTD Range	6	kyds
						Detection Range	80	kyds
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	2.95	0.002	Mean	2.762	0.002	Mean	1.25	0
Standard Error	0.037226	0.002	Standard Error	0.041643	0.002	Standard Error	0.041887	0
Median	3	0	Median	3	0	Median	1	0
Mode	3	0	Mode	3	0	Mode	1	0
Standard Deviation	0.832398	0.04472136	Standard Deviation	0.931177	0.04472136	Standard Deviation	0.936619	0
Sample Variance	0.692886	0.002	Sample Variance	0.86709	0.002	Sample Variance	0.877255	0
Kurtosis	0.020281	500	Kurtosis	-0.57714	500	Kurtosis	-0.6988	0
Skewness	-0.53401	22.3606798	Skewness	-0.30234	22.36067977	Skewness	0.320486	0
Range	4	1	Range	4	1	Range	4	0
Minimum	0	0	Minimum	0	0	Minimum	0	0
Maximum	4	1	Maximum	4	1	Maximum	4	0
Sum	1475	1	Sum	1381	1	Sum	625	0
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.061345	0.00329583	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.068625	0.003295826	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.069026	<0.001
Confidence(90%) of more than 99% chance of survivability	0.938655	0.99670417	Confidence(90%) of more than 99% chance of survivability	0.931375	0.996704174	Confidence(90%) of more than 99% chance of survivability	0.930974	>0.99
Results	**Fail**	**Pass**	Results	**Fail**	**Pass**	Results	**Fail**	**Pass**

Option 19 (1,2,3,4,5,6,7)		
Payload/Component Changes		
Upgrade missile type		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Upgrade ATTD		
Upgrade Sensor		
Upgrade Decoy		
Input Changes from Baseline		
BI P(Kill)	0.95	
RCS	2.5	
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.4	
ATTD Range	6	kyds
Detection Range	80	kyds
Decoy P(Kill)	0.5	
Statistics		
	AWS	Frigate
Mean	1.206	0
Standard Error	0.038394	0
Median	1	0
Mode	1	0
Standard Deviation	0.858509	0
Sample Variance	0.737038	0
Kurtosis	-0.14755	0
Skewness	0.392201	0
Range	4	0
Minimum	0	0
Maximum	4	0
Sum	603	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.063269	<0.001
Confidence(90%) of more than 99% chance of survivability	0.936731	>0.99
Results	**Fail**	**Pass**

Option 20 (1,2,4,5)		
Payload/Component Changes		
Upgrade missile type		
RCS improvement to ship & payload design		
Upgrade ATTD		
Input Changes from Baseline		
BI P(Kill)	0.95	
RCS	2.5	
ATTD P(Kill)	0.95	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0.004	0
Standard Error	0.002826	0
Median	0	0
Mode	0	0
Standard Deviation	0.063182	0
Sample Variance	0.003992	0
Kurtosis	247.4839	0
Skewness	15.76369	0
Range	1	0
Minimum	0	0
Maximum	1	0
Sum	2	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.004656	<0.001
Confidence(90%) of more than 99% chance of survivability	0.995344	>0.99
Results	**Pass**	**Pass**

Option 21 (2, 4, 5)		
Payload/Component Changes		
RCS improvement to ship & payload design		
Upgrade ATTD		
Input Changes from Baseline		
RCS	2.5	
ATTD P(Kill)	0.95	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0.192	0
Standard Error	0.017858	0
Median	0	0
Mode	0	0
Standard Deviation	0.399318	0
Sample Variance	0.159455	0
Kurtosis	1.074265	0
Skewness	1.66309	0
Range	2	0
Minimum	0	0
Maximum	2	0
Sum	96	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.029429	<0.001
Confidence(90%) of more than 99% chance of survivability	0.970571	>0.99
Results	**Fail**	**Pass**

Option 22 (2, 3, 4, 5)		
Payload/Component Changes		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Upgrade ATTD		
Input Changes from Baseline		
RCS	2.5	
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.95	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0.26	0
Standard Error	0.021016	0
Median	0	0
Mode	0	0
Standard Deviation	0.469938	0
Sample Variance	0.220842	0
Kurtosis	1.168533	0
Skewness	1.497789	0
Range	2	0
Minimum	0	0
Maximum	2	0
Sum	130	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.034633	<0.001
Confidence(90%) of more than 99% chance of survivability	0.965367	>0.99
Results	**Fail**	**Pass**

Option 23 (2,3,4,5,9)		
Payload/Component Changes		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Upgrade ATTD		
Install 3rd ATTD onboard each ship		
Input Changes from Baseline		
RCS	2.5	
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.95	
ATTD Range	10	kyds
Statistics		
	AWS	Frigate
Mean	0.012	0
Standard Error	0.004874	0
Median	0	0
Mode	0	0
Standard Deviation	0.108994	0
Sample Variance	0.01188	0
Kurtosis	79.14671	0
Skewness	8.990558	0
Range	1	0
Minimum	0	0
Maximum	1	0
Sum	6	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.008033	<0.001
Confidence(90%) of more than 99% chance of survivability	0.991967	>0.99
Results	**Pass**	**Pass**

Option 24 (2,3,4,5,9)		
Payload/Component Changes		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Upgrade ATTD		
Install 3rd ATTD onboard each ship		
Input Changes from Baseline		
RCS	2.5	
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.8	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0.018	0
Standard Error	0.005952	0
Median	0	0
Mode	0	0
Standard Deviation	0.133084	0
Sample Variance	0.017711	0
Kurtosis	51.09539	0
Skewness	7.272621	0
Range	1	0
Minimum	0	0
Maximum	1	0
Sum	9	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.009808	<0.001
Confidence(90%) of more than 99% chance of survivability	0.990192	>0.99
Results	**Pass**	**Pass**

Option 25 (2,4,5,9)			Option 26 (2,4,5,9)			Option 27 (3, 4, 5)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
RCS improvement to ship & payload design			RCS improvement to ship & payload design			Upgrade Main Gun		
Upgrade ATTD			Upgrade ATTD			Upgrade ATTD		
Install 3rd ATTD onboard each ship			Install 3rd ATTD onboard each ship					
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
RCS	2.5		RCS	2.5		Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.95		ATTD P(Kill)	0.8		ATTD P(Kill)	0.8	
ATTD Range	10	kyds	ATTD Range	12	kyds	ATTD Range	12	kyds
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	0.008	0	Mean	0.164	0.018	Mean	0.792	0
Standard Error	0.003988	0	Standard Error	0.017053	0.005951709	Standard Error	0.033402	0
Median	0	0	Median	0	0	Median	1	0
Mode	0	0	Mode	0	0	Mode	1	0
Standard Deviation	0.089173	0	Standard Deviation	0.381307	0.13308427	Standard Deviation	0.746895	0
Sample Variance	0.007952	0	Sample Variance	0.145395	0.017711423	Sample Variance	0.557852	0
Kurtosis	121.2289	0	Kurtosis	2.846944	51.09538678	Kurtosis	-0.36233	0
Skewness	11.07899	0	Skewness	2.035971	7.272621235	Skewness	0.561141	0
Range	1	0	Range	2	1	Range	3	0
Minimum	0	0	Minimum	0	0	Minimum	0	0
Maximum	1	0	Maximum	2	1	Maximum	3	0
Sum	4	0	Sum	82	9	Sum	396	0
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.006572	<0.001	Confidence Level(90.0%) of less than 1% chance of losing an AWS	0.028101	0.009807899	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.055044	<0.001
Confidence(90%) of more than 99% chance of survivability	0.993428	>0.99	Confidence(90%) of more than 99% chance of survivability	0.971899	>0.99	Confidence(90%) of more than 99% chance of survivability	0.944956	>0.99
Results	**Pass**	**Pass**	Results	**Fail**	**Pass**	Results	**Fail**	**Pass**

Option 28 (3, 4, 5, 6)			Option 29 (3, 4, 5, 7)			Option 30 (3, 4, 5, 9)		
Payload/Component Changes			Payload/Component Changes			Payload/Component Changes		
Upgrade Main Gun			Upgrade Main Gun			Upgrade Main Gun		
Upgrade ATTD			Upgrade ATTD			Upgrade ATTD		
Upgrade Decoy			Upgrade Sensor			Install 3rd ATTD onboard each ship		
Input Changes from Baseline			Input Changes from Baseline			Input Changes from Baseline		
Main Gun P(Kill)	0.6		Main Gun P(Kill)	0.6		Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.8		ATTD P(Kill)	0.8		ATTD P(Kill)	0.95	
ATTD Range	12	kyds	ATTD Range	12	kyds	ATTD Range	10	kyds
Decoy P(Kill)	0.5		Detection Range	80	kyds			
Statistics			Statistics			Statistics		
	AWS	Frigate		AWS	Frigate		AWS	Frigate
Mean	0.784	0	Mean	0.012	0	Mean	0.014	0
Standard Error	0.033897	0	Standard Error	0.004874	0	Standard Error	0.00526	0
Median	1	0	Median	0	0	Median	0	0
Mode	1	0	Mode	0	0	Mode	0	0
Standard Deviation	0.757953	0	Standard Deviation	0.108994	0	Standard Deviation	0.117608	0
Sample Variance	0.574493	0	Sample Variance	0.01188	0	Sample Variance	0.013832	0
Kurtosis	-0.43402	0	Kurtosis	79.14671	0	Kurtosis	67.12411	0
Skewness	0.576681	0	Skewness	8.990558	0	Skewness	8.297929	0
Range	3	0	Range	1	0	Range	1	0
Minimum	0	0	Minimum	0	0	Minimum	0	0
Maximum	3	0	Maximum	1	0	Maximum	1	0
Sum	392	0	Sum	6	0	Sum	7	0
Count	500	500	Count	500	500	Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.055859	<0.001	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.008033	<0.001	Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.008667	<0.001
Confidence(90%) of more than 99% chance of survivability	0.944141	>0.99	Confidence(90%) of more than 99% chance of survivability	0.991967	>0.99	Confidence(90%) of more than 99% chance of survivability	0.991333	>0.99
Results	**Fail**	**Pass**	Results	**Pass**	**Pass**	Results	**Pass**	**Pass**

Option 31 (3, 4, 5, 9)		
Payload/Component Changes		
Upgrade Main Gun		
Upgrade ATTD		
Install 3rd ATTD onboard each ship		
Input Changes from Baseline		
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.8	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0.014	0.016
Standard Error	0.00526	0.00561704
Median	0	0
Mode	0	0
Standard Deviation	0.117608	0.12560076
Sample Variance	0.013832	0.01577555
Kurtosis	67.12411	58.1076884
Skewness	8.297929	7.73791133
Range	1	1
Minimum	0	0
Maximum	1	1
Sum	7	8
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.008667	0.00925639
Confidence(90%) of more than 99% chance of survivability	0.991333	0.99074361
Results	**Pass**	**Pass**

Option 32 (4, 5,6)		
Payload/Component Changes		
Upgrade ATTD		
Upgrade Decoy		
Input Changes from Baseline		
ATTD P(Kill)	0.95	
ATTD Range	10	kyds
Decoy P(Kill)	0.5	
Statistics		
	AWS	Frigate
Mean	0.158	0
Standard Error	0.017282	0
Median	0	0
Mode	0	0
Standard Deviation	0.386438	0
Sample Variance	0.149335	0
Kurtosis	4.439773	0
Skewness	2.290901	0
Range	2	0
Minimum	0	0
Maximum	2	0
Sum	79	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.028479	<0.001
Confidence(90%) of more than 99% chance of survivability	0.971521	>0.99
Results	**Fail**	**Pass**

Option 33 (4, 5,7)		
Payload/Component Changes		
Upgrade ATTD		
Upgrade Sensor		
Input Changes from Baseline		
ATTD P(Kill)	0.95	
ATTD Range	10	kyds
Detection Range	80	kyds
Statistics		
	AWS	Frigate
Mean	0.014	0
Standard Error	0.00526	0
Median	0	0
Mode	0	0
Standard Deviation	0.117608	0
Sample Variance	0.013832	0
Kurtosis	67.12411	0
Skewness	8.297929	0
Range	1	0
Minimum	0	0
Maximum	1	0
Sum	7	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.008667	<0.001
Confidence(90%) of more than 99% chance of survivability	0.991333	>0.99
Results	**Pass**	**Pass**

Option 34 (4, 5,7)		
Payload/Component Changes		
Upgrade ATTD		
Upgrade Sensor		
Input Changes from Baseline		
ATTD P(Kill)	0.8	
ATTD Range	12	kyds
Detection Range	80	kyds
Statistics		
	AWS	Frigate
Mean	0.01	0
Standard Error	0.004454	0
Median	0	0
Mode	0	0
Standard Deviation	0.099598	0
Sample Variance	0.00992	0
Kurtosis	95.97919	0
Skewness	9.879032	0
Range	1	0
Minimum	0	0
Maximum	1	0
Sum	5	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.00734	<0.001
Confidence(90%) of more than 99% chance of survivability	0.99266	>0.99
Results	**Pass**	**Pass**

Option 35 (4, 5,9)		
Payload/Component Changes		
Upgrade ATTD		
Install 3rd ATTD onboard each ship		
Input Changes from Baseline		
ATTD P(Kill)	0.8	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0.002	0
Standard Error	0.002	0
Median	0	0
Mode	0	0
Standard Deviation	0.044721	0
Sample Variance	0.002	0
Kurtosis	500	0
Skewness	22.36068	0
Range	1	0
Minimum	0	0
Maximum	1	0
Sum	1	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.003296	<0.001
Confidence(90%) of more than 99% chance of survivability	0.996704	>0.99
Results	**Pass**	**Pass**

Option 36 (4, 5,9)		
Payload/Component Changes		
Upgrade ATTD		
Install 3rd ATTD onboard each ship		
Input Changes from Baseline		
ATTD P(Kill)	0.95	
ATTD Range	10	kyds
Statistics		
	AWS	Frigate
Mean	0	0
Standard Error	0	0
Median	0	0
Mode	0	0
Standard Deviation	0	0
Sample Variance	0	0
Kurtosis	0	0
Skewness	0	0
Range	0	0
Minimum	0	0
Maximum	0	0
Sum	0	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	<0.001	<0.001
Confidence(90%) of more than 99% chance of survivability	>0.99	>0.99
Results	**Pass**	**Pass**

Option 37 (1, 8)		
Payload/Component Changes		
Upgrade CMS		
Upgrade missile type		
Input Changes from Baseline		
Launch Interval	1	sec
BI P(Kill)	0.95	
Statistics		
	AWS	Frigate
Mean	1.784	0.056
Standard Error	0.042595	0.01029271
Median	2	0
Mode	2	0
Standard Deviation	0.952449	0.23015199
Sample Variance	0.907158	0.05296994
Kurtosis	-0.51451	13.0586624
Skewness	0.1499	3.8738151
Range	4	1
Minimum	0	0
Maximum	4	1
Sum	892	28
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.070193	0.01696149
Confidence(90%) of more than 99% chance of survivability	0.929807	0.98303851
Results	**Fail**	**Fail**

Option 38 (1,2,8)		
Payload/Component Changes		
Upgrade CMS		
Upgrade missile type		
RCS improvement to ship & payload design		
Input Changes from Baseline		
Launch Interval	1	sec
BI P(Kill)	0.95	
RCS	2.5	
Statistics		
	AWS	Frigate
Mean	2.166	0.014
Standard Error	0.045619	0.005259594
Median	2	0
Mode	2	0
Standard Deviation	1.020061	0.117608092
Sample Variance	1.040525	0.013831663
Kurtosis	-0.37067	67.12411057
Skewness	-0.08693	8.29792914
Range	4	1
Minimum	0	0
Maximum	4	1
Sum	1083	7
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.075175	0.008667353
Confidence(90%) of more than 99% chance of survivability	0.924825	0.991332647
Results	**Fail**	**Pass**

Option 39 (1,2,3,8)		
Payload/Component Changes		
Upgrade CMS		
Upgrade missile type		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Input Changes from Baseline		
Launch Interval	1	sec
BI P(Kill)	0.95	
RCS	2.5	
Main Gun P(Kill)	0.6	
Statistics		
	AWS	Frigate
Mean	2.214	0
Standard Error	0.041326	0
Median	2	0
Mode	2	0
Standard Deviation	0.924073	0
Sample Variance	0.853912	0
Kurtosis	-0.30629	0
Skewness	-0.13121	0
Range	4	0
Minimum	0	0
Maximum	4	0
Sum	1107	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.068101	<0.001
Confidence(90%) of more than 99% chance of survivability	0.931899	>0.99
Results	**Fail**	**Pass**

Option 40 (1,2,3,4,5,8)		
Payload/Component Changes		
Upgrade CMS		
Upgrade missile type		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Upgrade ATTD		
Input Changes from Baseline		
Launch Interval	1	sec
BI P(Kill)	0.95	
RCS	2.5	
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.6	
ATTD Range	6	kyds
Statistics		
	AWS	Frigate
Mean	1.176	0
Standard Error	0.040365	0
Median	1	0
Mode	1	0
Standard Deviation	0.902581	0
Sample Variance	0.814653	0
Kurtosis	-0.41882	0
Skewness	0.417674	0
Range	4	0
Minimum	0	0
Maximum	4	0
Sum	588	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	0.066517	<0.001
Confidence(90%) of more than 99% chance of survivability	0.933483	>0.99
Results	**Fail**	**Pass**

Option 41 (1,2,3,4,5,8)		
Payload/Component Changes		
Upgrade CMS		
Upgrade missile type		
RCS improvement to ship & payload design		
Upgrade Main Gun		
Upgrade ATTD		
Input Changes from Baseline		
Launch Interval	1	sec
BI P(Kill)	0.95	
RCS	2.5	
Main Gun P(Kill)	0.6	
ATTD P(Kill)	0.95	
ATTD Range	12	kyds
Statistics		
	AWS	Frigate
Mean	0	0
Standard Error	0	0
Median	0	0
Mode	0	0
Standard Deviation	0	0
Sample Variance	0	0
Kurtosis	0	0
Skewness	0	0
Range	0	0
Minimum	0	0
Maximum	0	0
Sum	0	0
Count	500	500
Confidence Level(90.0%) of less than 1% chance of losing an AWS and a Frigate	<0.001	<0.001
Confidence(90%) of more than 99% chance of survivability	>0.99	>0.99
Results	**Pass**	**Pass**

APPENDIX I. COST-EFFECTIVENESS RESULTS

Table 16. Cost-Effectiveness Summary Results

	Baseline Payload	Payload upgrades	Payload Cost Total	Topside Sizing model		Frigate Ship Parameters				Vessel Cost Total	Overall Cost per frigate
	($M)	($M)	($M)	Pass/Fail	Design Buffer(m)	Length(m)	Beam(m)	Draught(m)	Displacement (tonnes)	($M)	Cost($M)
Option 1	161.2	10	171.2	Pass	4.99	127.5	15.7	4.23	3807	414.375	585.575
Option 2	161.2	15	176.2	Pass	6.92	126.7	15.6	4.21	3740	411.775	587.975
Option 3	161.2	8	169.2	Pass	3.94	127	15.6	4.22	3770	412.75	581.95
Option 4	161.2	6	167.2	Pass	6.53	126.8	15.6	4.21	3744	412.1	579.3
Option 5	161.2	6	167.2	Pass	6.53	126.8	15.6	4.21	3744	412.1	579.3
Option 6	161.2	8	169.2	Pass	6.05	126.7	15.6	4.21	3742	411.775	580.975
Option 7	161.2	10	171.2	Pass	6.96	127.1	15.6	4.22	3772	413.075	584.275
Option 8	161.2	10	171.2	Pass	6.92	126.7	15.6	4.21	3740	411.775	582.975
Option 9	161.2	25	186.2	Pass	4.99	127.5	15.7	4.23	3807	414.375	600.575
Option 10	161.2	18	179.2	Pass	2.00	127.8	15.7	4.24	3838	415.35	594.55
Option 11	161.2	16	177.2	Pass	7.01	127.5	15.7	4.23	3812	414.375	591.575
Option 12	161.2	33	194.2	Pass	2.00	127.8	15.7	4.24	3838	415.35	609.55
Option 13	161.2	31	192.2	Pass	4.54	127.5	15.7	4.23	3812	414.375	606.575
Option 14	161.2	35	196.2	Pass	7.66	127.8	15.7	4.25	3840	415.35	611.55
Option 15	161.2	39	200.2	Pass	4.02	127.8	15.7	4.25	3842	415.35	615.55
Option 16	161.2	39	200.2	Pass	4.02	127.8	15.7	4.25	3842	415.35	615.55
Option 17	161.2	39	200.2	Pass	4.02	127.8	15.7	4.25	3842	415.35	615.55
Option 18	161.2	49	210.2	Pass	4.30	128.2	15.8	4.26	3874	416.65	626.85
Option 19	161.2	57	218.2	Pass	3.44	128.2	15.8	4.26	3876	416.65	634.85
Option 20	161.2	75	236.2	Pass	4.58	127.7	15.7	4.24	3828	415.025	651.225
Option 21	161.2	65	226.2	Pass	6.52	126.9	15.6	4.22	3761	412.425	638.625
Option 22	161.2	73	234.2	Pass	4.14	127.3	15.7	4.23	3791	413.725	647.925
Option 23	161.2	80	241.2	Pass	4.14	127.3	15.7	4.23	3791	413.725	654.925
Option 24	161.2	74	235.2	Pass	4.14	127.3	15.7	4.23	3791	413.725	648.925
Option 25	161.2	72	233.2	Pass	6.52	126.9	15.6	4.22	3761	412.425	645.625
Option 26	161.2	66	227.2	Pass	6.52	126.9	15.6	4.22	3761	412.425	639.625
Option 27	161.2	42	203.2	Pass	3.60	127.3	15.7	4.23	3791	413.725	616.925
Option 28	161.2	50	211.2	Pass	2.74	127.3	15.7	4.23	3793	413.725	624.925
Option 29	161.2	52	213.2	Pass	3.81	127.6	15.7	4.24	3823	414.7	627.9
Option 30	161.2	65	226.2	Pass	3.60	127.3	15.7	4.23	3791	413.725	639.925
Option 31	161.2	59	220.2	Pass	3.60	127.3	15.7	4.23	3791	413.725	633.925
Option 32	161.2	46	207.2	Pass	5.73	127	15.6	4.22	3763	412.75	619.95
Option 33	161.2	48	209.2	Pass	6.79	127.3	15.7	4.23	3793	413.725	622.925
Option 34	161.2	44	205.2	Pass	6.79	127.3	15.7	4.23	3793	413.725	618.925
Option 35	161.2	51	212.2	Pass	6.38	126.7	15.6	4.21	3761	411.775	623.975
Option 36	161.2	57	218.2	Pass	6.38	126.7	15.6	4.21	3761	411.775	629.975
Option 37	161.2	20	181.2	Pass	4.99	127.5	15.7	4.23	3807	414.375	595.575
Option 38	161.2	35	196.2	Pass	4.99	127.5	15.7	4.23	3807	414.375	610.575
Option 39	161.2	43	204.2	Pass	2.00	127.8	15.7	4.24	3838	415.35	619.55
Option 40	161.2	49	210.2	Pass	1.55	127.8	15.7	4.25	3842	415.35	625.55
Option 41	161.2	93	254.2	Pass	1.57	128	15.8	4.25	3859	416	670.2

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